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THE EFFECT OF OILING AND AIR CELL MOLD ON THE OXYGEN AND CARBON DIOXIDE CONTENTS OF THE AIR CELLS OF EGGS[1]

BY DYSON ROSE AND N. E. GIBBONS

Abstract

The gas contained in the air cells of day old eggs had a high carbon dioxide content, but during storage the gas composition approached that of the surrounding atmosphere. Oiling of the egg, or otherwise sealing the shell, tended to retain carbon dioxide in the air cell. Growth of mold in the air cell, or of bacteria in the egg contents, markedly reduced the oxygen content and increased the carbon dioxide content of the air cell gas. Permeability of the shell of unoiled eggs to moisture vapor was low and the relative humidity in the air cell was shown to be 99% or higher. Oiling of the eggs cannot therefore promote mold growth by increasing the humidity in the air cell.

Introduction

In the spring of 1945 Canada stored a large number of oiled eggs for shipment to England during the fall and early winter months. Shortly after these eggs arrived, complaints were received of mold growth, visible on candling, in the air cells. These growths occurred at the air cell line and were usually limited to a small area even after prolonged storage. Occasionally greater growth occurred and it was observed that cracking or otherwise puncturing the shell, in the region of the air cell, promoted growth of the mold, sometimes to such an extent that the air cell was filled. Moran and Piqué (3) found mold of the genera *Penicillium* and *Cladosporium* in the air chamber of a storage egg, presumably unoiled, and Moran (2, p. 39) also states that "if mould grows within a sealed egg, it is generally first observed in the region of the air cell".

Since Canadian egg inspectors did not recall having seen air cell mold in untreated storage eggs,* oiling apparently had increased its occurrence and it was assumed that sealing the shell was in some way responsible. However, the increased storage life of oiled eggs warranted continued use of the oiling process. Although increasingly strict attention to the known principles of handling shell eggs has reduced the losses due to air cell mold, an investigation

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* *Private communication.*

of this form of spoilage and of the contributing factors was believed desirable. This paper presents data concerning the gas composition and relative humidity of the air cells of oiled and unoiled eggs, and a subsequent paper will evaluate the effect of pH and carbon dioxide on the growth of mold in eggs.

Eggs when laid contain carbon dioxide in equilibrium with that of the hen's body, and have no air cell (4, p. 147). As the egg cools, the contents shrink away from the shell, forming an air space which fills with carbon dioxide from the egg contents and with air drawn in from the outside. Loss of carbon dioxide, as well as of moisture, occurs during storage, leaving the egg contents alkaline, and additional air diffuses into the air cell so that the composition of the gas in the air cell tends to approximate that of the surrounding atmosphere. Romijn and Roos (5) found that the oxygen content of an unincubated egg was slightly over 20% and the carbon dioxide content was about 1.5%. In eggs in which the embryo is not developing, the rate at which the gas composition approaches that of the atmosphere depends on factors affecting the solubility of carbon dioxide, on the porosity of the shell, and on the presence or absence of sealing agents used to prolong the storage life of the egg.

Methods

Analysis of the air cell gas was accomplished as follows. The egg, with the air cell uppermost, was placed in a breaking chamber under a magnetically suspended plunger, and the chamber air was displaced with dibutyl phthalate from a leveling bulb. The plunger was then released, breaking the shell, and the gas that collected over the dibutyl phthalate was drawn into a closed system which had been previously evacuated to a pressure of 10^{-4} mm. of mercury. The gas, on being drawn into the system, passed through a $-70°$ C. cold trap to remove water and dibutyl phthalate vapor and was collected in a gas burette by means of a mercury diffusion pump connected to a Toepler pump. The pressure exerted by the gas at the fixed volume of the gas burette was read in millimeters of mercury, and the gas was then released from the top of the burette and passed over copper (wire form copper oxide reduced by hydrogen) at 550° C. to remove the oxygen. The residual gas was again collected in the gas burette and its pressure at fixed volume determined. It was released again to pass through a liquid air trap to remove carbon dioxide and then collected and the pressure measured. The temperature adjacent to the gas burette was also noted; this temperature was usually constant over the 30 min. period required for each determination.

From these data the total volume of the gas, and thus of the air cell, was calculated directly, and the volume of oxygen and carbon dioxide by difference between the residual volumes at each stage. Oxygen and carbon dioxide are reported as percentages of the total volume.

The apparatus was not suitable for moisture determinations and it was therefore necessary to estimate the relative humidity of the air cell by indirect

methods. Eggs ranging in weight from 51.6 to 67.2 gm. and having approximately the same sized air cells were used. The shell covering the air cell area was removed carefully with an abrasive wheel in a hand drill. The other two membranes were removed as desired by carefully cutting out the required area. The relative effect of the shell and of the shell plus egg membranes was then determined by measuring the loss in weight from these eggs during storage for 14 days at room temperature over saturated calcium nitrate solutions (50–55% R.H.).

Results and Discussion

Mold-free eggs

To study the effect of sealing agents on the composition of the air cell gas, commercial eggs were oiled at room temperature and stored, together with unoiled controls, at −1.1° C. (30° F.). The gas from four eggs was analyzed after 12, 18, and 24 weeks. The data presented in Table I show the expected

TABLE I

VOLUME (ML.) OF AIR CELLS OF EGGS STORED AT −1.1° C.

(Averages for four eggs)

Storage period, weeks	Untreated	Oiled	Oil + vasoline
12–13	2.3	1.4	1.4
18–19	3.6	1.9	1.6
24–25	4.0	2.3	1.7

Necessary difference for significance, 5% level—0.6 ml.

increase in air cell volume of the untreated and, to a lesser extent, the oiled eggs, but this increase in eggs treated with oil plus vasoline was less than the experimental error. The composition of the air cell gas varied considerably from egg to egg even within treatments, presumably as a result of the variable porosity of egg shells (1), and differences in carbon dioxide content did not attain statistical significance. However, the oxygen content (Table II)

TABLE II

OXYGEN CONTENT (%) OF AIR CELLS OF EGGS STORED AT −1.1° C.

(Averages for four eggs)

Storage period, weeks	Untreated	Oiled	Oil + vasoline	Average
12–13	19.5	17.4	18.3	18.4
18–19	20.0	17.9	18.9	18.9
24–25	20.0	19.9	19.2	19.7
Average	19.8	18.4	18.8	

Necessary difference for significance, 5% level:
—between averages for storage times—0.9%;
—between averages for treatments—0.9%.

showed a significant increase with time when averaged over all three treatments, and also a significant effect of treatment when averaged over storage times. Somewhat less oxygen diffused into the treated eggs than into the untreated eggs, but the two treatments did not differ significantly.

Since the commercial eggs used in the foregoing experiment were probably several days old and had already lost much carbon dioxide before oiling, a small additional trial was carried out on day old eggs. These eggs, oiled and unoiled, were stored at 15.6° C. (60° F.), to accelerate the changes, and analyzed after five weeks. The data for individual eggs are presented in Table III. Owing to the large variability between eggs, the differences in

TABLE III

VOLUME, OXYGEN, AND CARBON DIOXIDE CONTENT OF AIR CELLS OF EGGS TREATED WHEN ONE DAY OLD AND STORED AT 15.6° C. FOR FIVE WEEKS

(Values for individual eggs)

Treatment	Volume, ml.	Oxygen, %	Carbon dioxide, %
Untreated	3.2	18.9	−0.3
	3.3	20.3	0.4
	2.6	20.1	0.7
	2.9	16.7	1.8
	Av. 3.0	19.0	0.7
Oiled	0.6	18.0	1.9
	0.6	18.3	2.7
	0.6	18.0	3.6
	0.6	17.3	0.0
	0.8	17.4	0.1
	Av. 0.6	17.8	1.7

average oxygen and carbon dioxide contents between oiled and unoiled eggs were not statistically significant, but the data do suggest that, in the unoiled eggs, the composition of the air cell gas had more nearly approached that of the atmosphere. The carbon dioxide content of several of the oiled eggs is also suggestive of the high levels that are presumed to be present initially. Unfortunately the volume of the air cell of freshly laid eggs is not sufficient to allow analysis by this technique.

Eggs that had been subjected to various sealing treatments and stored in the laboratory at −1.1° C. for prolonged periods were also analyzed. The results, presented in Table IV, indicate that the better sealing treatments retained more carbon dioxide in the air cell. Also, carbon dioxide which had been added to the egg by gassing before oiling was partially retained even after storage for a year.

TABLE IV

VOLUME, OXYGEN, AND CARBON DIOXIDE CONTENT OF AIR CELLS OF EGGS STORED AT −1.1° C. FOR APPROXIMATELY ONE YEAR

(Averages for three eggs)

Treatment	Volume, ml.	Oxygen, %	Carbon dioxide, %
Untreated	5.9	19.0	1.0
Oil + magnesium stearate	1.2	16.1	2.2
Oil + vasoline	1.1	15.0	3.9
Carbon dioxide + oil	1.4	12.4	7.5

Eggs with Air Cell Mold

Mold growing in the air cell must utilize oxygen and produce carbon dioxide, and if diffusion of these gases through the shell is restricted a marked change in the composition of the air cell gas would be expected. Such changes are clearly shown by the data obtained by analysis of both commercial and laboratory stored eggs (Table V). The extremely low oxygen content of these eggs suggests that lack of oxygen is responsible for the limited growth of mold usually found.

TABLE V

VOLUME, OXYGEN, AND CARBON DIOXIDE CONTENT OF AIR CELLS OF EGGS FROM COMMERCIAL AND LABORATORY STORAGE

Treatment	Age (approx.)	Number of eggs	Volume, ml.	Oxygen, %	Carbon dioxide, %
Commercial storage					
Oiled	6 mos.	5	1.2	18.6	0.2
Oiled, with air cell mold	6 mos.	18	1.3	2.3	4.3
Laboratory storage					
Oiled	2 yrs.	3	3.5	18.1	1.8
Oiled, with air cell mold	2 yrs.	3	4.3	0.4	11.1

Occasionally analytical data were obtained from apparently normal eggs which were similar to those reported for eggs having air cell mold. Examination of the contents of some of these eggs indicated large numbers of bacteria although there were no visible signs of spoilage. Data for three eggs which were apparently undergoing incipient spoilage are presented in Table VI.

TABLE VI

VOLUME, OXYGEN, AND CARBON DIOXIDE CONTENT OF AIR CELLS OF EGGS UNDERGOING INCIPIENT SPOILAGE

(Values for individual eggs)

Storage temp., °C.	Storage period, weeks	Volume, ml.	Oxygen, %	Carbon dioxide, %
15.6	6–7	3.4	2.0	6.6
− 1.1	18–19	2.0	2.3	1.9
− 1.1	24–25	1.5	17.5	3.5

Humidity Relations

Sharp and Stewart (6) state that the egg is in equilibrium with a relative humidity of 99.5%. They do not state how this figure was obtained, but a similar figure (99.6%) can be calculated from the freezing point of albumen (−0.45° C., reference 8, p. 155). If the shell is the main barrier to the outward passage of water vapor from the egg, the relative humidity in the air cell should approximate this figure.

The effects of removing the shell and the egg membranes on the rate of diffusion of water vapor out of the egg are shown in Table VII. The loss of weight is expressed in milligrams per square centimeter of opening through

TABLE VII

LOSS OF MOISTURE THROUGH AIR CELL AREA

(Averages for six eggs exposed for 14 days at 50–55% R.H.)

Treatment	Loss, mgm./sq. cm./24 hr.
Intact eggs	1.6
Shell only removed	11.6
Shell and shell membrane removed	12.2
Shell, shell membrane and egg membrane removed	11.4

the shell per 24 hr. and is corrected for the loss through the intact portion of the shell, the area of the egg being calculated from the formula $S = \frac{BP\pi}{2}$ (4, p. 109), where S is the surface area, B the breadth, and P the long circumference. These data indicate that diffusion of water vapor is markedly restricted by the shell itself but not by the membranes.

Smith (7, pp. 86-95) arrived at the same conclusion by slightly different methods, and it is therefore apparent that even in untreated eggs the relative humidity of the air cell must approach 99.5%. Oiling the egg further reduces the permeability of the shell to moisture vapor, and thus may increase the humidity slightly, but the difference cannot be great enough to influence the growth of mold.

Acknowledgments

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References

1. ALMQUIST, H. J. and HOLST, W. F. Hilgardia, 6: 61-72. 1931.
2. MORAN, T. Report of Food Investigation Board for 1937. His Majesty's Stationery Office, London. 1938.
3. MORAN, T. and PIQUÉ, J. Food Investigation Board. Special Report No. 26. His Majesty's Stationery Office, London. 1926.
4. ROMANOFF, A. L. and ROMANOFF, H. J. The avian egg. John Wiley and Sons, Inc., New York. 1949.
5. ROMIJN, C. and ROOS, J. J. Physiol. 94: 365-379. 1938.
6. SHARP, P. F. and STEWART, G. F. Cornell Univ. Agr. Expt. Sta. Mem. No. 191: 1-11. 1936.
7. SMITH, A. J. M. Report of the Food Investigation Board for 1930. His Majesty's Stationery Office, London. 1931.
8. SMITH, A. J. M. Report of the Food Investigation Board for 1931. His Majesty's Stationery Office, London. 1932.

ENTEROCOCCI AS AN INDEX OF FECAL CONTAMINATION IN EGG PRODUCTS[1]

By Helen J. Brown[2] and N. E. Gibbons[2]

Abstract

Enterococci were present in all samples of liquid and frozen egg products examined. They survived spray drying and storage in egg powder better than the coliforms and *Escherichia coli* and are therefore considered a better index of fecal contamination. There was no relation between the occurrence of *Salmonella* organisms and the number of enterococci present. *Streptococcus faecalis* was the species most commonly found. The addition of 0.5% yeast extract to SF medium reduced the number of false negatives and improved the sensitivity, although confirmation on agar was still necessary. Winter and Sandholzer's medium, with bromocresol purple as indicator, could be used without confirmation but was not as sensitive for products containing small numbers of enterococci.

Introduction

Escherichia coli, the usual index of fecal contamination of food products, has been found unsatisfactory for dried egg products. Little relation was noted between the total viable, coliform, or *E. coli* counts (6) or between these counts and the presence of *Salmonella* organisms in Canadian egg powder (3), although most of these organisms, other than *S. pullorum*, are now considered to come from fecal material on the shells. The *E. coli* test was found to be of little value in determining the presence or absence of *Salmonella* organisms in high moisture egg powder manufactured in the United States, although a correlation was observed between the plate count averages of *E. coli* positive samples and the degree of *E. coli* contamination (19). In low moisture egg powders, more *Salmonella* organisms were isolated from *E. coli* negative samples than from *E. coli* positive samples (9).

Because of the limitations of the *E. coli* test a number of investigators have considered the use of the enterococci or Group D streptococci as an index of fecal pollution of water and of various food products. The sanitary significance of the streptococci in water has been discussed by others (13, 14). In a comparative study of enterococci and *E. coli* as indices of fecal pollution of a number of food products (11) an excellent correlation was found between sanitary conditions during preparation and the recovery of both *E. coli* and enterococci from the product.

The occurrence of both of these organisms in liquid and frozen egg products appears to be of sanitary significance because melange prepared in the laboratory under carefully controlled conditions contained negligible numbers of both types, while commercial melange from plants where the breakers allowed

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the egg meat to run over the shell often contained large numbers of both *E. coli* and enterococci.

The presence of enterococci in liquid egg for drying into powder takes on added significance when the possibility of these heat resistant organisms surviving the drying process is considered. If they survive to a greater extent than *E. coli* they should provide a more accurate indication of the original condition of the melange than do *E. coli*.

Since enterococci are invariably present in chicken feces, according to our studies and those of other investigators (10, 15), and since they are heat resistant (17), it was felt that a more definite relation might be established between the enterococcus content of spray dried egg powder and the occurrence of other organisms of fecal origin. This paper presents evidence supporting the use of enterococci as an index of fecal contamination of egg products, particularly egg powder.

Materials and Methods

The egg powders used in part of this work were composite carlot samples used in a previous investigation (2), while other samples were received directly from the drying plants or purchased in retail stores. Several samples of sugar–egg powder (12) were obtained from the control laboratory of the Dominion Department of Agriculture. Liquid egg samples were obtained from a local breaking plant and frozen egg samples from a local distributor.

To determine the effect of spray drying and subsequent storage on the various organisms, melange was prepared from fresh eggs and inoculated just before drying with 18-hr. broth cultures of the following organisms: *Aerobacter* species and *E. coli* from chicken feces, *Streptococcus faecalis* isolated from commercial melange, and *Salmonella bareilly* from dried egg powder. The melange (approximately 4°–5° C.) was then dried in an experimental spray drier, the average air inlet temperature being 116° C. and the average air outlet temperature being 65° C. The powder was mixed, stored at 21° and 10° C. and samples removed at intervals for the determination of the inoculated organisms.

Bacteriological Methods

Total viable counts were made by plating with tryptone glucose agar and incubating at 32° C. for 72 hr. (1). The numbers of enterococci, coliforms, *E. coli*, and *Salmonella* organisms in the various products were estimated by the most probable number (M.P.N.) technique. At least three dilutions of each sample (usually containing 1.0, 0.1, and 0.01 gm. of powder or of liquid egg) were each inoculated into 10 tubes containing 10 ml. of medium. When the inoculum was 5.0 ml. (1 gm. powder) or greater, the strength of the medium was adjusted to maintain the correct concentrations of the ingredients. The M.P.N. per gram of product was calculated from the values given in the tables for water (1). The 10 tubes of each dilution are considered as duplicate sets of five.

Brilliant green bile, 2%, was used to estimate the M.P.N. of coliforms (1). Tubes showing gas formation were streaked on eosin methylene blue agar and the M.P.N. of *E. coli* estimated. For estimating *Salmonella* organisms, appropriate dilutions were made in tetrathionate broth and positive tubes detected by streaking on Bacto SS agar (3).

Sherman's classification of the Group D streptococci (17) was followed in the identification of the enterococci. Gram-positive diplococci or short chained streptococci were considered to be enterococci if they grew at 10° C. and at 45° C., grew in the presence of 6.5% sodium chloride and at pH 9.6, rapidly reduced litmus milk before curdling, and reduced 0.1% methylene blue in skim milk. Broth (0.5% proteose peptone, 0.5% tryptone), adjusted after autoclaving to pH 9.6 with *N* sodium hydroxide, was used to determine the tolerance to high alkalinity and proved as satisfactory as a highly buffered liquid medium (16). The heat tolerance of a number of strains was tested and all survived 30 min. at 60° C. Species of enterococci were differentiated on the basis of hemolysis on horse blood agar and liquefaction of gelatin.

Development of Suitable Media

In the earlier work, Hajna and Perry's SF medium (5) with incubation at 45° C. for 72 hr. was used to isolate the enterococci. It soon became apparent that a number of tubes gave false negative reactions, i.e., showed no acid production but contained typical enterococci. More of these false negative reactions were observed in tubes which contained the smaller amounts of egg powder, apparently indicating a lack of nutrients. To compensate for this deficiency, 0.5% yeast extract was added to the basic SF medium. This medium, hereinafter referred to as SFY medium, appeared to produce a sharper color change and to reduce the number of false negatives.

The medium suggested by Winter and Sandholzer (20) for a presumptive test for enterococci was also used, but the indicator was changed to bromocresol purple as it was impossible to detect changes with the original bromothymol blue when egg products were used. Color changes due to growth of enterococci continued up to 72 hr., therefore this longer incubation period was adopted. With these modifications the color changes were clear cut, false negatives rarely occurred, and there appeared to be less opportunity for low acid producing bacteria to interfere with the test. Although it has been reported (8) that *B. subtilis* may cause considerable trouble through false positives in Winter's medium, Gram-positive, spore forming rods have been observed in positive tubes only twice with the modified Winter's and once with the SF medium and on each occasion they occurred in combination with enterococci.

All tubes showing acid production were considered positive for enterococci. Confirmation was carried out at the end of the incubation period by streaking representative positive tubes and all negative tubes on tryptone glucose agar. The plates were incubated at 45° C. for 18–24 hr. Since the enterococci usually

occurred in pure culture in the three media with all types of egg products a selective medium was not necessary for the confirmatory tests. The presence of characteristic round, raised colonies, pin point to 1 mm. in diameter, gray to milky in color, consisting of Gram-positive diplococci or short chained streptococci was considered a positive test for enterococci. Typical colonies were isolated for taxonomic study.

Statistical examination of the observed and confirmed enterococcus counts by the three media on 17 samples of egg powder showed that there was a difference (5% level of significance) between the two counts with SF and SFY media but not with Winter's medium (Table I). An analysis of variance

TABLE I

OBSERVED AND CONFIRMED ENTEROCOCCUS COUNTS PER GRAM OF EGG POWDER AS DETERMINED WITH THREE MEDIA
(Average values for 17 samples)

Medium	Log count per gram		Necessary difference, 5% level
	Observed	Confirmed	
SF	2.21	2.52	0.16
SFY	2.40	2.61	0.12
Winter's	2.52	2.56	0.14

showed that the variation between the two counts within samples was significant with SF medium but not with the SFY medium. The addition of yeast extract has therefore improved the original medium by reducing the variation and giving more predictable results.

Confirmed counts on the same series of samples show that the relation between the counts on SF medium (x) and on SFY medium (y) was $y = 0.946x + 0.221$ (Fig. 1). There was no significant difference between the means of

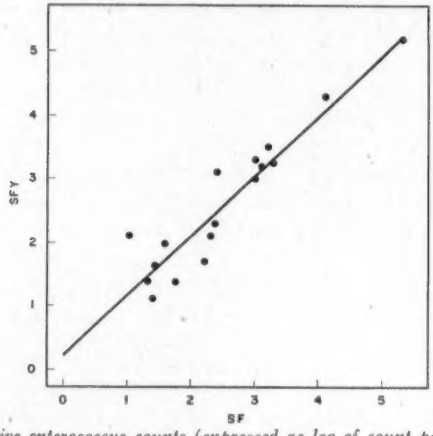

FIG. 1. *Comparative enterococcus counts (expressed as log of count per gram) of egg powder using SF and SFY media.*

the counts by the two methods and the slope of the line ($b = 0.95$) did not differ significantly from unity. With less than 100 organisms per gram the values obtained on Winter's medium were very irregular when compared with those on SF medium. By omitting these low values the relation was described by the equation $y = 0.996x + 0.267$ when y is the count on Winter's medium and x is the count on SF medium (Fig. 2). The slope of this line ($b = 0.92$) did not differ significantly from unity and there was no significant difference between the means of the counts.

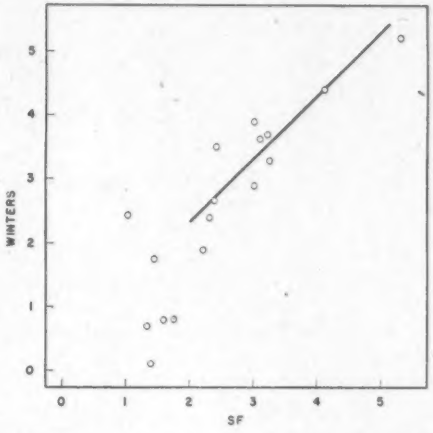

FIG. 2. *Comparative enterococcus counts (expressed as log of count per gram) of egg powder using SF and Winter's media.*

Although there is little difference in the confirmed counts on the three media, in use the modified media are superior to the original SF media in several respects. The SFY medium is more sensitive, fewer tubes have to be confirmed, and the confirmed count could be predicted, if necessary, from the observed count. The modified Winter's medium is reliable for counts greater than 100 per gram, and the added labor of confirming the initial count is eliminated. It should be quite satisfactory for control work. However, for investigational work the more sensitive medium with confirmation seems desirable, and in this paper all the enterococcus counts reported are confirmed results with SFY medium unless otherwise stated.

Results

The total viable, coliform, *E. coli*, and enterococcus counts for a number of samples of liquid and frozen egg are given in Table II. There seems to be little relation between high total and coliform counts and the number of enterococci or *E. coli* in liquid egg, but the frozen egg samples with lower viable counts contained correspondingly fewer coliforms, *E. coli*, and enterococci. In another series of six samples of frozen egg the log of the number of entero-

TABLE II

BACTERIAL CONTENT OF LIQUID AND FROZEN EGG SAMPLES
(Log of count per gram)

Material	Total viable	Coliforms	*E. coli*	Enterococci
Liquid whole egg	6.84	2.54	0.9	0.72
	6.33	2.54	0.02	0.88
	6.12	2.54	0.0	1.70
	6.04	4.54	1.43	0.50
	5.64	2.54	2.54	2.54
	5.62	4.52	4.52	3.54
Frozen whole egg + yolk	4.62	0.38	0.38	$\bar{1}$.76
	4.44	0.52	0.13	$\bar{1}$.30
	4.04	2.80	2.80	0.49
	3.78	$\bar{1}$.3	$\bar{1}$.3	0.82
	2.90	$\bar{1}$.3	$\bar{1}$.3	$\bar{1}$.6
Frozen sugared yolk	6.49	3.25	3.25	3.52
	6.23	4.56	4.56	2.05
	6.07	3.56	3.56	3.50

cocci per gram ranged from $\bar{1}$.96 to 1.63. Although *E. coli* was occasionally absent from these samples, enterococci were always found.

The effect of spray drying on the survival of various organisms is shown in Table III. The percentage reduction is based on the assumption that one gram of powder is equivalent to four grams of liquid egg. The *E. coli* were destroyed completely and over 99% of the *Salmonella* and coliforms were killed, confirming earlier findings (4). In contrast the survival of over 40% of the enterococci indicates the value of these organisms as an index of fecal contamination.

TABLE III

EFFECT OF SPRAY DRYING ON THE BACTERIAL CONTENT OF EGG POWDER

(Reduction based on assumption that
1 gm. powder = 4 gm. liquid egg)

Organism	Liquid, count per gm.	Powder, count per gm.	Reduction, %
Total viable count	60,000	6800	97.17
Coliforms	7100	20	99.93
E. coli	15,000	0	100.00
Salmonella bareilly	8900	7	99.98
Streptococcus faecalis	1100	1800	59.09

The survival of the different organisms after storage of the egg powder at 21° and 10° C. is shown in Fig. 3. At 21° C., the coliforms and *Salmonella* organisms died off rapidly, dropping to less than one per gram by the end of the first week. Neither was detected after two weeks' storage, but the number of enterococci had decreased only slightly after 12 weeks. At 10° C. the

Salmonella and coliform count dropped to less than one per gram after four and six weeks respectively. The enterococci were still present in almost undiminished numbers after 18 weeks.

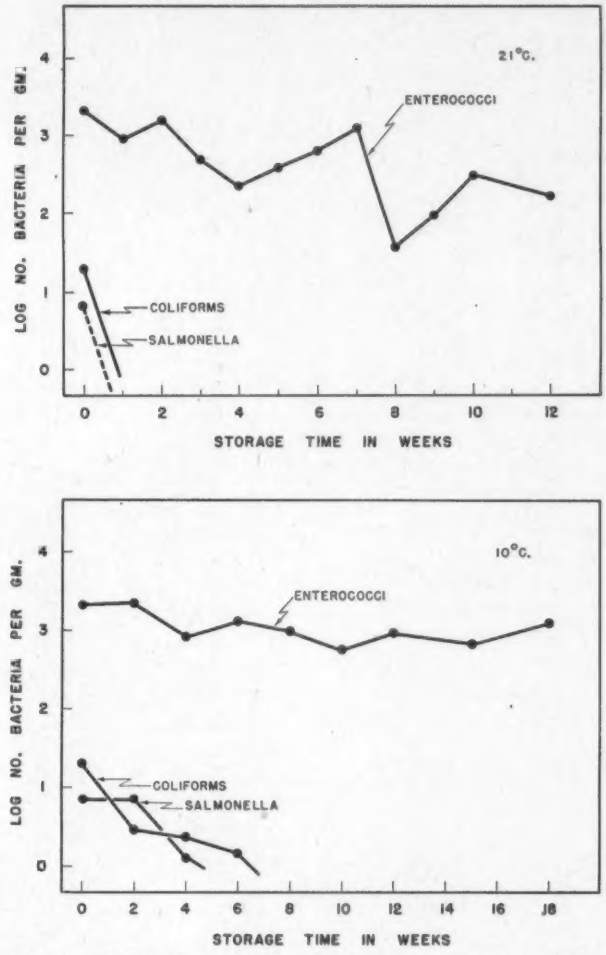

FIG. 3. *Effect of storage at 21° and 10° C. on the enterococcus, coliform and Salmonella counts of egg powder.*

Results obtained with commercially produced powders substantiate these findings. In a series of 160 samples of whole egg powders and 24 samples of sugar–egg powders, enterococci were found in relatively large numbers in every sample, while 32.5% of the whole egg powders and 33.3% of the sugar–egg powders were negative for *E. coli*. An additional 27.5% of the whole egg

powders and 41.7% of the sugar-egg powders contained less than one *E. coli* organism per gram.

The bacterial content of 23 of the samples of whole egg powder was studied in more detail. In Fig. 4 the enterococcus counts are arranged in descending order with their corresponding total viable and coliform counts. The total

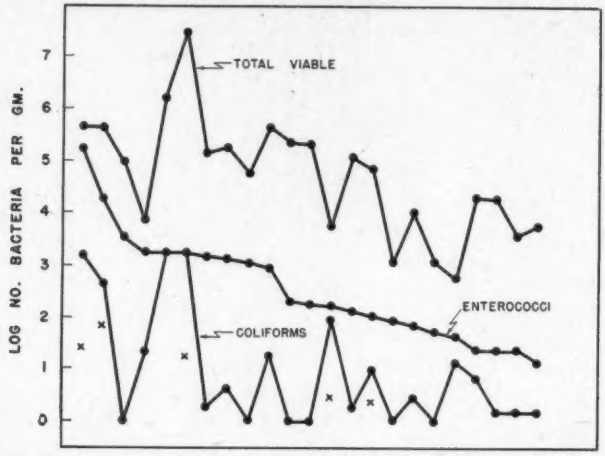

FIG. 4. *Relation between enterococcus counts of whole egg powder and the corresponding total viable and coliform counts. x indicates count of E. coli in positive samples.*

viable counts ranged from 30 million to 600 per gram, the enterococcus counts from 170,000 to 13 per gram, and the coliform count from 1800 to less than one per gram. Only 10 samples were positive for *E. coli* and the highest count was 72 per gram. Of these only five contained more than one per gram and these are shown as isolated points on the figure. Although there was consider-

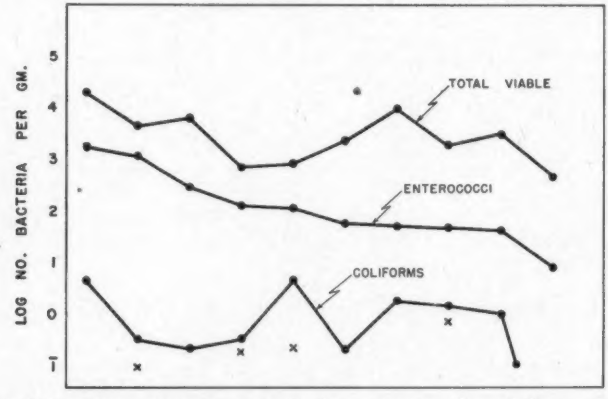

FIG. 5. *Relation between enterococcus counts of sugar-egg powder and the corresponding total viable and coliform counts. x indicates count of E. coli in positive samples.*

able variation, a general relation exists between high enterococcus counts and high total viable counts. The relation between enterococcus and coliform counts is less apparent. Most of the samples positive for *E. coli* fell among those with the higher enterococcus counts.

A similar series of counts for 10 samples of sugar–egg powder is presented in Fig. 5. These powders had been stored at −18° to −23° C. for 18 months when the tests were made, but the enterococci appeared to have survived storage. The total viable and the enterococcus counts are related, but little relation exists between these counts and the number of coliforms, *E. coli*. *Salmonella* organisms (1.25 per gm.) were found in only one sample.

The data from an earlier investigation were combined with the present results in a further effort to gain some information about the conditions present in egg powder containing organisms of the *Salmonella* group. These are presented in Table IV. The data on enterococci in the second part of the table were obtained with SF media without confirmation and the counts are probably

TABLE IV

COMPARISON OF ENTEROCOCCUS, COLIFORM, AND *E. coli* COUNTS FROM EGG POWDERS POSITIVE AND NEGATIVE FOR *Salmonella* ORGANISMS

Material	Medium used for enterococcus detn.	Number of samples	Count per gram					
			Enterococci		Coliforms		*E. coli*	
			Average	Range	Average	Range	Average	Range
Salmonella positive	SF and SFY confirmed	17	250	54–1800	14	0–48	2	0–8
Salmonella negative		49	4240	8–170,000	124	0–1800	3	0–70
Salmonella positive	SF unconfirmed	20	29	2–180	45	0–180	8	0–90
Salmonella negative		90	58	2–180	19	0–160	5	0–160

lower than when confirmation is carried out. The coliform and *E. coli* counts were estimated by the same method in both investigations. In both series higher enterococcus counts were found in the *Salmonella* negative samples. The same relation holds even if the highest enterococcus count (170,000 per gram) is omitted from the *Salmonella* negative series. There was a similar lack of relation between high coliform and *E. coli* counts and the occurrence of *Salmonella* organisms.

Species of Enterococci in Egg Products

Typical enterococcus colonies were picked from the confirmatory plates and identified according to Sherman's scheme for the classification of the entero-

cocci (17). The distribution of the four species in three types of egg products and in chicken feces is summarized in Table V. Most of the enterococci were nonhemolytic, and *S. faecalis* was by far the commonest species found in both egg products and chicken feces, followed by *S. liquefaciens*, *S. durans*, and

TABLE V

DISTRIBUTION OF ENTEROCOCCI ISOLATED FROM EGG PRODUCTS AND CHICKEN FECES

Source	Number of cultures	*S. faecalis*, %	*S. liquifaciens*, %	*S. durans*, %	*S. zymogenes*, %
Liquid egg	31	87.1	6.5	3.2	3.2
Frozen egg	23	43.5	26.1	8.7	21.7
Dried egg	124	72.6	22.6	4.0	0.8
Chicken feces	16	62.5	18.75	18.75	0.0

S. zymogenes. Many of the *S. faecalis* and *S. liquefaciens* cultures produced a slight greening of horse blood agar, but only those cultures showing marked beta-hemolysis were considered to be *S. durans* or *S. zymogenes*. The same sample often contained more than one species.

The proportions of the four species are of course subject to great variation but since the material under study was collected from a wide variety of sources over a long period of time, it is felt that the figures represent a reasonably characteristic pattern.

Discussion

Enterococci have been found in all samples of liquid, frozen, and dried egg examined. Most of the enterococci survive drying and there is little decrease in numbers during storage. Since they survive 30 min. at 60° C., they should also survive preheating and possibly pasteurization. On the other hand, although *E. coli* and the coliforms are usually present in liquid egg, it has been shown that their numbers are greatly reduced by spray drying and that they die off rapidly in stored powder. The enterococci are therefore considered a much better index of fecal contamination in egg products than the coliforms.

Although enterococci are probably always present in chicken feces, *Salmonella* organisms are present only in material from infected flocks, and a correlation between the presence of *Salmonella* organisms and high enterococcus counts therefore could hardly be expected. Although it has been shown that more *Salmonella* organisms are present on the shells of dirty eggs than on clean eggs (18), it is evident that dirty eggs from flocks free of *Salmonella* infection would not harbor these organisms. However, the careless poultryman who allows the production of dirty eggs is probably careless about the health of his flock also.

Since enterococci usually occur in small numbers and are lost in the usual plating procedure, selective media are essential for their detection. Failure to isolate enterococci regularly from egg powder (7) can probably be attributed

to this fact. For investigational purposes the more sensitive SFY medium seems preferable. For routine examinations, the modified Winter's medium would be sufficiently reliable, since it can be used for counts of 100 per gram or over without further confirmation.

Acknowledgments

The authors are indebted to Dr. C. K. Johns of the Central Experimental Farm who supplied many of the samples; to Mr. D. Fletcher of the Special Products Board, Department of Agriculture, who arranged for supplies of egg powder from the processors; and to the producers themselves for generous samples. Mr. H. Gunner, working earlier in these laboratories, obtained the data on 110 samples shown in the latter part of Table IV. The technical assistance of Miss M. Brownlie is gratefully acknowledged.

References

1. American Public Health Association. Standard methods for the examination of dairy products. 9th ed. American Public Health Assoc. New York. 1948.
2. Gibbons, N. E. Can. J. Research, F, 25: 291-298. 1947.
3. Gibbons, N. E. and Moore, R. L. Can. J. Research, F, 22: 48-57. 1944.
4. Gibbons, N. E. and Moore, R. L. Can. J. Research, F, 22: 58-63. 1944.
5. Hajna, A. A. and Perry, C. A. Am. J. Pub. Health, 33: 550-556. 1943.
6. Johns, C. K. Sci. Agr. 24: 373-382. 1944.
7. Johns, C. K. and Berard, H. L. Sci. Agr. 25: 551-565. 1945.
8. McCormack, G. Am. J. Pub. Health, 39: 516. 1949.
9. McFarlane, V. H. and Calesnick, F. J. Poultry Sci. 27: 87-90. 1948.
10. Ostrolenk, M. and Hunter, A. C. J. Bact. 51: 735-741. 1946.
11. Ostrolenk, M., Kramer, N. and Cleverdon, R. C. J. Bact. 53: 197-203. 1947.
12. Pearce, J. A., Brooks, J., and Tessier, H. Can. J. Research, F, 24: 420-429. 1946.
13. Prescott, S. C., Winslow, C. E. A., and McCrady, M. H. Water bacteriology. 6th ed. John Wiley & Sons, Inc., New York. 1946.
14. Ritter, C. and Treece, E. L. Am. J. Pub. Health, 38: 1532-1538. 1948.
15. Shapiro, S. K. and Sarles, W. B. J. Bact. 58: 531-544. 1949.
16. Shattock, P. M. F. and Hirsch, A. J. Path. Bact. 59: 495-497. 1947.
17. Sherman, J. M. Bact. Revs. 1: 3-97. 1937.
18. Solowey, M., Spaulding, E. H., and Goresline, H. E. Food Research, 11: 380-390. 1946.
19. Sutton, R. R. and McFarlane, V. H. Food Research, 12: 474-483. 1947.
20. Winter, C. E. and Sandholzer, L. A. U.S. Fish Wildlife Service, Commercial Fisheries Technological Leaflet, 2: 1-3. 1946.

PRESERVATION OF EGGS

VII. EFFECT OF AGE OF EGG AND CARBON DIOXIDE CONTENT AT TIME OF OILING ON KEEPING QUALITY[1]

By N. E. GIBBONS[2]

Abstract

The quality of eggs oiled when one day old is maintained better than that of eggs oiled when 6 or 10 days old, the ages between which most commercial eggs are treated. If the pH of the albumen of the older eggs is lowered by exposure to carbon dioxide before oiling (a simple method of treating eggs with carbon dioxide is described), the keeping quality as measured by yolk index, albumen height, and percentage of thick albumen is improved. However, these differences are not apparent on candling, and on this basis the improvement does not justify the added cost of the gassing treatment.

Introduction

After an egg is laid the pH of the albumen rises from about 7.6 to about 9.5 over a period of two to three days owing to the loss of carbon dioxide. If this loss can be prevented and the pH maintained at 8 or slightly lower, the internal quality of the egg is preserved much better during storage.

Two methods of maintaining the pH have been tried: gas treatment and oiling. The pH may be maintained by storing the eggs in an atmosphere containing carbon dioxide (8) but this method has never found wide application, probably because of the elaborate facilities needed. The correct pH may also be obtained by oiling the eggs 18 to 24 hr. after laying (2, 12) when part of the natural carbon dioxide has escaped. Oiling too quickly results in an egg with too low a pH with subsequent thinning of the thin white. Under the present system of collection, oiling 18 to 24 hr. after laying necessitates treatment on the farm (6) but this has some disadvantages in Canada since at the present time only eggs stored for export are oiled, a small percentage of the total production.

For older eggs these two methods may be combined, i.e., part of the carbon dioxide may be replaced by exposure to an atmosphere of carbon dioxide for a time prior to oiling (10), but the methods suggested so far have been elaborate (13) and have not been adopted commercially although better keeping quality results (5, 9, 13).

When the experiments reported in this paper were made, the average age of eggs oiled commercially was 7 to 10 days, by which time most of the carbon dioxide had been lost (14). This paper describes the effect of age of eggs

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before oiling on the preservation of quality, the development of a simple method of gassing the eggs, and the effect of replacing the carbon dioxide in market eggs.

Materials and Methods

For preliminary experiments, eggs less than 24 hr. old were obtained from the Poultry Division, Central Experimental Farm, Ottawa, and oiled immediately or stored at 50° F. until oiled, or gassed and oiled.

For the early experiments reported here, one-day-old eggs were obtained from a producer whose eggs had been used in previous tests (4) and oiled immediately or after holding for 6 or 10 days at 50° F. At each time one third of the eggs were left unoiled, one third were oiled, and one third exposed to 10% carbon dioxide for 24 hr. before oiling. The eggs were stored at 70° F. and a R.H. of approximately 40% to accelerate changes, and 12 eggs from each treatment examined after 4, 8, and 12 weeks.

For all later experiments, eggs obtained at a local grading station were used as representative of the eggs being oiled for commercial storage.

The oils used throughout the investigation met Canadian specifications (1). In the laboratory an oil previously found satisfactory was used (4, Oil *E*). The eggs were given a 5 to 10 sec. dip in oil held at room temperature.

The eggs were weighed individually before and after storage to determine moisture loss. To determine internal quality the eggs were candled, then broken out on a level glass plate and the yolk index (3), albumen height, pH, and the percentage of inner thin, outer thin, and thick albumen measured. The albumen fractions were determined by transferring the egg to a brass screen (14 mesh, 26 S.W.G.) and weighing the outer thin fraction that passes through. The inner thin fraction was collected separately after slashing the thick white. The thick portion was then separated from the yolk and transferred to a beaker for weighing.

A Method of Gassing Eggs

In the early experiments the eggs were gassed in desiccators by evacuating the necessary amount of air and replacing with carbon dioxide. In later tests a sheet metal tank, 2.5 ft. square and 5 ft. deep was used. The heavier carbon dioxide was admitted into the bottom of the tank and the air was expelled through a vent in the lid. In this way concentrations ranging from 90% at the bottom to 70% near the top could be obtained. Up to four cases of eggs could be treated at once and the cases could be removed and others added with a loss of about half the gas. The gas content was checked periodically during the tests by removing samples from gas cocks installed at different levels and analyzing the gas in an Orsat–Lunge apparatus.

Experiments indicated that the rate of decrease in pH of the white was proportional to the concentration of carbon dioxide (Fig. 1). With con-

centrations of 60% to 70% the pH could be lowered to 7.8 in about an hour. Some eggs are more resistant to the penetration of carbon dioxide and it was found that the eggs should be exposed at least 1.5 hr. to ensure all being below pH 8.0. After one hour exposure to 90% carbon dioxide, eggs having an initial pH of 9.1 had a pH of 7.55. After one, two and five hours at room

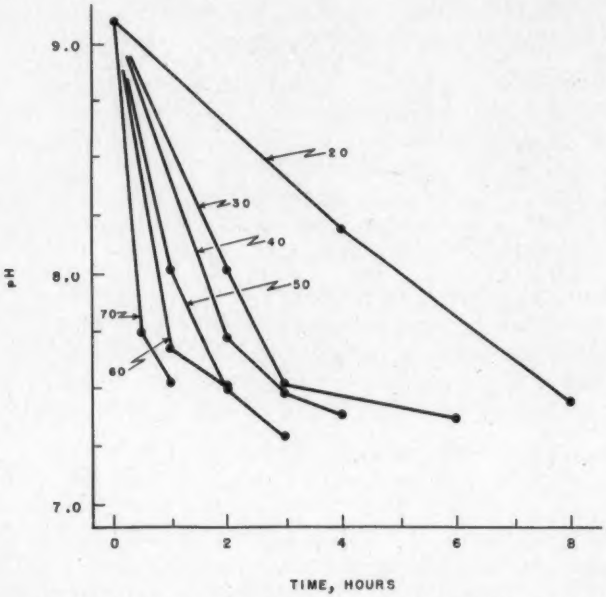

FIG. 1. *The effects of various concentrations of carbon dioxide from 20% to 70% on lowering of pH of the albumen of shell eggs.*

temperature the pH of the white was 7.6, 8.0, and 8.3 respectively, an increase similar to that reported by others (14). Although it has been reported (2, 12) that a greater proportion of thin albumen develops in eggs oiled at a pH below 8.0, this was not noted here (cf. Table I) and the eggs were oiled soon after gassing.

Results

In the preliminary experiments, the indications were that when older eggs were oiled, their quality was not maintained as well on storage. When older eggs were treated with carbon dioxide before oiling, their quality on storage was about equal to that of day-old oiled eggs.

In the first experiment reported the one- and six-day-old unoiled eggs, when candled after eight weeks at 70° F., were grade *C* with a few slightly adhering yolks; the 10-day-old eggs were in much worse condition and quality measurements could be made on only four of 12 eggs. There was considerable evaporation and large air cells developed. In the oiled eggs the one- and

TABLE I

EFFECT OF OILING 1-, 6-, AND 10-DAY-OLD EGGS BEFORE AND AFTER COMING TO EQUILIBRIUM WITH 10% CARBON DIOXIDE, AND STORING AT 70° F.

Treatment and storage time, weeks	Weight loss, gm.		Yolk index	Albumen height, in.	pH	Percentage albumen		
	Before treating	After treating				Outer thin	Inner thin	Thick
One day old								
Initial	—	—	0.450	0.27	8.85	26.7	27.6	45.7
Unoiled								
4	—	4.3	0.293	0.10	9.21	84.6	2.7	12.7
8	—	8.5	0.184	0.08	9.29	96.1	0	3.9
12	—	13.1	0.145*	0.08*	9.24*	97.3*	0*	2.7*
Oiled								
4	—	0.4	0.366	0.17	8.48	50.4	20.0	29.6
8	—	0.6	0.345	0.14	8.33	52.9	12.6	34.5
12	—	1.4	0.278	0.10	8.62	73.7	1.6	24.7
CO_2 + oil								
Initial	—	—	0.443	0.25	7.51	33.1	19.6	47.2
4	—	0.3	0.444	0.25	7.92	47.7	18.1	34.2
8	—	0.6	0.405	0.20	8.22	59.3	8.7	32.0
12	—	1.3	0.348	0.18	8.64	56.6	12.4	31.0
Six days old								
Initial	0.4	—	0.430	0.19	9.15	35.1	23.3	41.6
Unoiled								
4	0.4	3.8	0.282	0.11	9.20	80.4	5.1	14.5
8	0.4	8.3	0.190	0.11	9.19	96.0	0	4.0
12	0.4	14.3	0.154*	0.08	9.32	88.8*	0*	11.2*
Oiled								
4	0.4	0.3	0.343	0.14	8.79	73.9	7.5	18.6
8	0.4	1.0	0.295	0.12	8.72	72.3	4.2	23.5
12	0.4	1.5	0.269	0.08	8.78	91.1	0	8.9
CO_2 + oil								
Initial	0.4	—	0.420	0.20	7.84	36.2	23.0	40.8
4	0.4	0.4	0.404	0.18	7.82	45.6	16.8	37.6
8	0.4	0.8	0.386	0.19	8.18	49.6	13.6	36.8
12	0.4	0.9	0.362	0.14	8.25	60.2	7.6	32.2
Ten days old								
Initial	0.5	—	0.412	0.19	9.21	37.5	25.4	37.1
Unoiled								
4	0.6	4.2	0.258	0.13	9.22	92.1	0	1.9
8	0.6	9.3	0.214*	0.10*	9.15*	94.0*	0*	6.0*
12	0.6	12.7	0.166*	0.11*	9.16*	89.2*	0*	10.8*
Oiled								
4	0.5	0.5	0.306	0.13	8.78	83.6	0	16.4
8	0.3	0.7	0.277*	0.12*	9.10	85.0	0*	15.0*
12	0.6	1.2	0.255*	0.06	8.62	90.4	0*	9.6*
CO_2 + oil								
Initial	0.2	—	0.424	0.22	7.71	33.4	23.0	43.6
4	0.4	0.3	0.417	0.22	7.67	50.4	14.5	35.1
8	0.4	0.6	0.398	0.19	8.09	53.9	13.2	32.9
12	0.3	0.9	0.347	0.14	8.42	54.3	6.5	39.1

**Average of six eggs or less due to stuck or weak yolks; others are averages of 12 eggs.*

TABLE II

EFFECT OF OILING EGGS AND OF TREATMENT WITH CARBON DIOXIDE BEFORE OILING ON VARIOUS QUALITY MEASUREMENTS

(Average values over age of egg and time of storage, from Table I)

Treatment	Yolk index	Albumen height, in.	pH	Percentage albumen	
				Outer thin	Inner thin
Unoiled	0.210	0.099	9.22	91.0	0.9
Oiled	0.304	0.117	8.69	74.8	5.1
CO_2 + oil	0.390	0.188	8.14	53.1	12.4
Necessary difference, 5% level	0.031	0.029	0.32	12.9	5.2

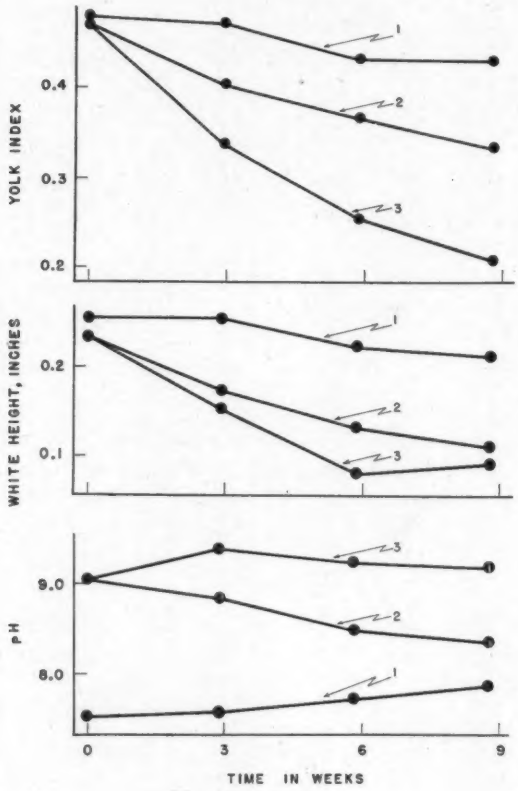

FIG. 2. *Changes in yolk index, albumen height, and pH of eggs treated with carbon dioxide before oiling (1), of oiled eggs (2), and of unoiled eggs (3), when stored at 70° F.*

six-day-old eggs graded *B* at eight weeks, whereas in the 12 10-day-old eggs there were eight stuck yolks. In the gassed eggs practically all the eggs graded *B* at both 8 and 12 weeks.

Some similar trends were noted in the quality measurements on the broken out eggs (Table I). With oiled eggs the yolk indices indicated that each increase in age of eggs before oiling shortened the storage life at 70° F. by several weeks. These differences are not apparent for the unoiled and the gassed eggs, and statistical analyses of the data indicated that the over-all differences due to age were not significant. However, the eggs treated with carbon dioxide before oiling were significantly better than the oiled eggs (Table II), and 10-day-old eggs so treated had better yolk indices, greater albumen heights, and more thick albumen than eggs oiled when one day old. In most quality measurements the oiled eggs were superior to the unoiled eggs.

Using the tank described earlier, eggs obtained from a local grading station were exposed to 90% carbon dioxide for an hour, then oiled and stored at 70° F. for three, six, and nine weeks. The results (Fig. 2) indicate that the gassed eggs maintained their quality much better than the oiled eggs or the unoiled controls. In the graph each point is the average value for 12 eggs. Measurements of this kind do not always indicate the difference in appearance of the broken out egg, and this is shown in Fig. 3. These photographs also show the clouding of the white in the gassed eggs.

Since in these and other laboratory trials the gassed and oiled eggs always had a much better appearance than the oiled eggs it was decided to make a commercial trial. Gas-tight tanks in which high concentrations of carbon dioxide could be maintained by admitting the gas at the bottom were installed at five oiling stations, and during the months of April and May, 1946, 9000 cases were gassed before oiling. Some of the tanks were not wholly satisfactory but the pH of several eggs from each run was checked, using pH papers sensitive round pH 7.8. Only when the samples showed values around this point were the eggs considered successfully gassed. The treated eggs were stored along with oiled eggs in the regular commercial storages at 30° F. and representative lots were examined in July, September, October, and November.

The candling results are summarized in Table III. Although the results are based on relatively few eggs the gassed eggs were slightly superior until the last sampling.

The average values obtained on the broken out eggs (Table III) also indicate that the gassed eggs were of better quality than the oiled. Throughout the tests it was quite evident that in the gassed eggs the yolks were rounder, the thick albumen thicker, and the general appearance better. Towards the last the thin white became watery but the appearance of gassed eggs was still better than that of oiled eggs. Examination of the eggs on arrival in England confirmed these findings. However, the improvement noted on

FIG. 3. *Appearance of broken out eggs treated with carbon dioxide and oil or with oil only, and of day old oiled eggs after three weeks' storage at 70° F.*

TABLE III

CANDLING GRADES AND QUALITY MEASUREMENTS ON EGGS GASSED AND OILED OR OILED ONLY AT OILING STATIONS IN APRIL AND MAY AND STORED IN COMMERCIAL STORAGES

(Candling grades expressed as percentages of number of eggs examined each month, other measurements as average values)

Measurements	Gassed and oiled				Oiled only			
	July	Sept.	October	Nov.	July	Sept.	October	Nov.
Candling grades								
A	86.3	93.5	90.1	34.6	79.0	90.0	83.3	39.2
B	11.4	5.3	9.5	59.9	18.6	9.9	12.5	56.1
C	1.4	0.5	0.4	2.3	1.3	0.0	0.5	2.7
Rejects	0.9	0.7	0.0	3.2	1.1	0.1	3.7	3.0
Yolk index	0.435	0.439	0.443	0.432	0.408	0.409	0.416	0.412
Albumen height	0.19	0.18	0.19	0.17	0.17	0.16	0.17	0.16
pH	7.97	8.25	8.14	8.29	8.68	8.65	8.63	8.59
No. eggs, doz.	25	32	37	26	25	16	18	13

candling was so slight that the extra expense (about 10 cents per case) was not warranted.

As improvement in the commercially treated eggs did not seem as great as in laboratory trials, 72 cases of commercial eggs were gassed in the laboratory and stored in a commercial storage at 30° F. and 80% R.H. for 23 weeks. Various concentrations of carbon dioxide were used since it was thought that in the commercial trials the concentrations may not have been controlled

TABLE IV

QUALITY TESTS ON EGGS EXPOSED TO VARIOUS CONCENTRATIONS OF CARBON DIOXIDE BEFORE OILING, AND THEN STORED FOR 23 WEEKS AT 30° F. AND 80% R.H.

Treatment	Yolk index		Albumen height, in.		pH of albumen	
	Initial	Final	Initial	Final	Initial	Final
Oiled only	0.451	0.425	0.19	0.16	9.00	8.54
40% CO_2 for 1.5 hr., oiled immediately	0.458	0.470	0.18	0.18	7.93	7.80
60% CO_2 for 1.5 hr., oiled immediately	0.446	0.450	0.21	0.17	7.68	7.83
80% CO_2 for 1.5 hr., oiled immediately	0.452	0.446	0.22	0.18	7.54	7.77
80% CO_2 for 1.5 hr., oiled 16 hr. later	0.461	0.441	0.20	0.17	8.21	8.02
80% CO_2 for 3 hr., oiled 16 hr. later	0.458	0.452	0.21	0.17	8.21	7.93
Necessary difference, 5% level		0.02	0.02		0.10	0.16

sufficiently. To prevent layering, the gas in the tank was circulated at all times by means of a circulating pump. Two lots were left overnight at room temperature (*ca.* 70° F.) before oiling to increase the pH to that of day-old eggs. The pH values of the albumen (Table IV) reflect the concentrations of carbon dioxide used. Gassing also increased the initial albumen height significantly probably owing to a shrinking phenomenon. After storage there was no significant difference in albumen height. There was also little difference in the amount of thin white in the various treatments although initially there was some indication of early thinning in the eggs treated with 80% carbon dioxide. The pH of the albumen of the gassed eggs remained significantly lower than that of the oiled eggs. The yolk indices of the treated eggs were usually significantly higher indicating that gassing prevented flattening of the yolk. However, these improvements could not be detected by candling, which showed no significant difference between any of the treatments (Table V).

TABLE V

CANDLING RESULTS ON EGGS EXPOSED TO VARIOUS CONCENTRATIONS OF CARBON DIOXIDE BEFORE OILING AND THEN STORED FOR 23 WEEKS AT 30° F. AND 80% R.H.

Treatment	Percentage of						
	Grade *A*	Grade *B*	Grade *C*	Air cell mold	Internal mold	Rots	Cracks
Oiled only	67.6	29.4	0.5	0.0	0.03	0.4	1.0
40% CO_2 for 1.5 hr., oiled immediately	69.3	27.5	1.1	0.2	0.2	0.2	1.5
60% CO_2 for 1.5 hr., oiled immediately	70.0	25.7	2.3	0.02	0.1	0.4	1.5
80% CO_2 for 1.5 hr., oiled immediately	65.4	30.8	2.2	0.02	0.0	0.1	1.5
80% CO_2 for 1.5 hr., oiled 16 hr. later	63.0	33.0	1.7	0.0	0.0	0.3	1.9
80% CO_2 for 3 hr., oiled 16 hr. later	67.6	28.6	1.7	0.0	0.0	0.2	1.8

Discussion

It is difficult to reconcile the early laboratory results with those obtained in the commercial and the last laboratory experiments. In the early experiments the eggs were obtained when fresh and were held in the laboratory under good conditions with very little handling. The pregassing treatment of the commercial eggs was not known but the eggs had been handled several

times. This may have contributed to the poorer keeping quality: it has recently been shown that conditions between the farm and assembling points may have a measureable effect on quality (7).

The early storage tests were conducted at 70° F. and at this temperature four weeks' storage causes greater changes in yolk index and the other quality measurements than 40 weeks at 30° F. (4). This is about the proper relation if a Q_{10} of 1.8 to 2.0 is assumed. Under normal commercial conditions, storage for longer periods than six to seven months at 30° F. is not necessary, and it would seem that the periods used in the commercial trials were not long enough for differential trends to become apparent by candling. Others have shown that quality measurements based on a scoring system which included flavor and odor, as well as yolk index and condition of the albumen, had a much greater range in good quality eggs than could be detected by candling (11). The quality measurements used here are more sensitive than candling in detecting differences amongst good quality eggs. The possibility that the eggs were overgassed and that the poor candling results were due to thinning of the thin white is not substantiated by the results of the last experiment (Tables IV and V).

The only conclusion possible seems to be that the improvement noted in the broken out gassed eggs is not great enough to show up on candling and is therefore of no commercial importance. This may explain why gassing has not been adopted commercially.

Acknowledgments

I am indebted to Miss H. J. Brown who made many of the quality measurements, to Mr. S. Martin who made a number of the initial tests including the effect of gas concentration on the pH, and to Mr. S. C. Barry of the Special Products Board who arranged for the commercial trials and their financing.

References

1. Canada, Department of Agriculture. Special Products Board, Ottawa. Oil Specifications, Ref. No. 125. Feb. 1, 1946.
2. Evans, R. J. and Carver, J. S. U.S. Egg Poultry Mag. 48 : 546-549. 1942.
3. Gibbons, N. E. Can. J. Research, F, 25 : 18-21. 1947.
4. Gibbons, N. E., Michael, R., and Irish, U. Can. J. Research, F, 25 : 141-148. 1947.
5. Kaess, G. and Kiermeier, F. Tatigkeit des kaltetech. Inst. Karlsruhe, 1 Oct. 1937-31 Mar. 1939, p. 52.
6. Mallmann, W. L. and Davidson, J. A. Mich. Agr. Expt. Sta. Quarterly Bull. 26 : 309-312. 1944.
7. Miller, H. I. U.S. Egg Poultry Mag. 55 : 18-19, 24. 1949.
8. Moran, T. Food Investigation Leaflet No. 8. H.M. Stationery Office, London. 1939.
9. Rosser, F. T., White, W. H., Woodcock, A. H., and Fletcher, D. A. Can. J. Research, D, 20 : 57-70. 1942.
10. Sharp, P. F. Science, 69 : 278-280. 1929.
11. Stewart, G. F., Gans, A. R., and Sharp, P. F. U.S. Egg Poultry Mag. 39 : 37-39, 60, 61. 1933.
12. Stewart, G. F. and Bose, S. Poultry Sci. 27 : 270-276. 1948.
13. Swenson, T. L. Food Research, 3 : 599-608. 1938.
14. Wilhelm, L. A. U.S. Egg Poultry Mag. 46 : 397-401. 1940.

POLAROGRAPHIC DETERMINATION OF TITANIUM IN PAINT PIGMENTS

By B. R. Potts

Abstract

A simple, rapid polarographic procedure for the determination of titanium in paint pigments has been developed, using a sulphuric acid – tartaric acid medium. The accuracy and precision of the method are satisfactory for routine testing operations. The interference of other common pigment ingredients is discussed, and a procedure suggested for the removal of copper and antimony prior to analysis.

The standard volumetric method (2) for the determination of titanium in paint pigments, involving as it does solution in sulphuric acid, filtration, reduction, and titration with potassium permanganate, is subject to interference from a wide variety of substances which, under the conditions of test, yield compounds reactive toward permanganate. These substances include certain organic compounds, nitric acid, iron, chromium, antimony, arsenic, tin, molybdenum, vanadium, tungsten, uranium, and columbium. (5). In the analysis of pigments for titanium, iron and antimony are probably the most common sources of interference. Many methods are available for overcoming the interference of iron (5) but in most cases it is necessary to determine iron in a separate operation and correct the titanium result accordingly. Antimony may be removed by precipitation with hydrogen sulphide in acid solution. In routine testing operations, these procedures are time-consuming, and it was felt that a useful purpose would be served if a rapid direct polarographic procedure could be developed as an alternative for the established methods. Although the polarograph has usually been used as an instrument for microanalysis, there is nothing to prevent its being used in macromethods, provided that the precision required does not exceed that obtainable with this instrument.

Titanium produces a good wave in hydrochloric, sulphuric, or nitric acid medium, according to Kolthoff and Lingane (4); the half-wave potential is approximately −0.81 v. vs. the saturated calomel electrode. Zeltzer (6) suggested a procedure for the determination of titanium in minerals, using a sulphuric acid medium after fusion with potassium bisulphate. Useful waves may also be obtained in citric or tartaric acid solution, and Kolthoff and Lingane (4) report that sulphuric acid solutions of these two organic acids should be preferable in practical work. Recently Adams (1) reported that acid sodium oxalate solutions provided a good medium for the determination of titanium in clays and related materials. A pronounced maximum

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was obtained under these conditions, but was successfully suppressed by the addition of urea.

Zeltzer's method appeared to provide the most direct approach to the problem, and sulphuric acid was first tried as a medium for the titanium determination. Satisfactory waves were not obtained in this solution. (Adams, in the article previously mentioned, reports the same experience.) When tartaric acid was added to the solution, however, well defined waves were obtained. These waves did not exhibit any maxima, and this solution finally provided a satisfactory medium for the determination of titanium.

Apparatus

An E. H. Sargent & Co. Model XX polarograph was used in this work. The capillary was cut from a piece of marine barometer capillary tubing supplied by E. H. Sargent & Co. This rugged type of capillary has proved its worth in routine work, where danger of breakage is always present. An ordinary electrolysis cell with internal anode was used throughout. All wave heights were measured by the slope-intercept method. Temperature was maintained at $25 \pm 0.2°$ C. by means of a constant temperature cabinet modeled after that described by Borup and Levin (3).

Reagents

The reagents used were: concentrated sulphuric acid (sp. gr. 1.84); potassium bisulphate (Reagent Grade—crystals); acid tartaric (Reagent Grade), 25% solution; titanium dioxide (Reagent Grade).

Procedure

To 0.300 gm. of the dry pigment (0.100 gm. in the case of pure titanium oxide pigments) add 7 gm. of potassium bisulphate crystals and mix thoroughly. Add exactly 20 ml. of sulphuric acid, cover, heat to fumes of sulphur trioxide, and allow to fume for exactly 20 min., swirling occasionally. Cool, transfer to a 100 ml. volumetric flask, keeping sample and washings to less than 50 ml. Add exactly 50 ml. of tartaric acid solution, make up to the mark, and mix. Transfer a portion to a polarographic cell, deaerate, and polarograph. The titanium wave occurs at approximately -0.44 v. vs. the internal anode.

Titanium dioxide dissolves very slowly in sulphuric acid, and the process is accelerated greatly by the addition of an alkali sulphate. Ammonium sulphate was as effective as potassium bisulphate in this operation. Solution of the pigment may also be effected by fusing with potassium pyrosulphate and dissolving the melt in dilute sulphuric acid (1 : 4). This method, however, has the disadvantage of being too efficient—it puts into solution more of the substances likely to interfere with the determination of titanium than does the method outlined above. In the course of the digestion method

described in the procedure, many pigments do not appear to be completely in solution at the end of 20 min., but experience has shown that if the sample size is within the prescribed limits, all the titanium present will be in solution in this time. The insoluble compounds which remain do not interfere with the analysis, and it has been found unnecessary to filter the solution at this point. It is usually possible to decant the clear solution above the precipitate when transferring the sample to the polarographic cell.

The over-all time required for a single determination of titanium by this method is one hour. However, several samples may be run at the same time, each additional sample requiring about eight minutes. Filtration, an operation which is expensive both in equipment and in operators' time, is avoided, as is the maintenance of one or several Jones reductors, which are required in the usual method. No standard solutions are used, and, throughout the procedure, a considerable saving in time is effected.

The interference of other elements was studied at some length. Titanium dioxide frequently occurs in combination with barium sulphate and calcium sulphate, but since neither barium nor calcium discharge at a low enough potential to interfere with titanium, neither of these common substances presented a problem. Zinc oxide and lithopone, both having zinc as the active ingredient, do not interfere. Lead, iron, antimony, and copper all produce waves in tartaric acid solution, so that such substances as white lead, lead chromate, iron oxide, antimony oxide, and copper phthallocyanine might be expected to interfere. The preparation of the sample leaves lead precipitated as lead sulphate, so that no lead wave was observed. Chromium and iron were found to depress the diffusion current slightly if present in large amount, a property they share with aluminum. These three elements can be tolerated to a concentration of one third the concentration of titanium without producing an appreciable interference, while at a concentration of approximately two thirds that of titanium, the depression of the diffusion current is measurable and amounts to a little less than 2% of the titanium content. Cobalt does not interfere. Antimony and copper interfere directly, producing large waves at the same potential as titanium. Antimony usually gives rise to a maximum and other irregularities in the limiting current. If either or both of these elements are present, they may be quickly removed without impairing the accuracy of the method, as follows. Following the digestion period, the solution is diluted to approximately 100 ml., saturated with hydrogen sulphide, and the precipitated antimony and copper sulphides filtered off and washed with water saturated with hydrogen sulphide. The filtrate is boiled to remove hydrogen sulphide, and evaporated to a small enough volume to transfer to a 100 ml. flask. The sample is prepared and polarographed for titanium.

The effect of these various possible interfering substances on the titanium result will be found summarized in Table I. These figures were all obtained from artificial solutions prepared from reagent titanium dioxide which had

been analyzed by the standard procedure (2). The interfering substances were, wherever possible, used in the exact form in which they might be expected to appear in pigments. In cases where they were not available in such form, the salt used is indicated in the table in parentheses.

TABLE I

INTERFERENCE OF OTHER SUBSTANCES

Interfering substance	Ratio impurity: TiO_2	% TiO_2 present	% TiO_2 found	% error
Barium sulphate	2.0	33.3	33.2	−0.3
Calcium sulphate	2.0	33.3	33.3	0
Zinc oxide	2.0	33.3	33.5	+0.6
Lithopone	2.0	33.3	33.1	−0.6
Lead (oxide)	0.6	33.3	33.3	0
Lead chromate	0.3	33.3	33.4	+0.3
" "	0.6	33.3	32.7	−1.8
Chromic oxide	0.3	33.3	33.3	0
" "	0.6	33.3	33.1	−0.6
Iron oxide	0.3	33.3	33.5	+0.6
" "	0.6	33.3	32.6	−2.1
Aluminum (sulphate)	0.25	33.3	33.2	−0.3
" "	0.5	33.3	32.8	−1.5
Cobalt (sulphate)	0.5	33.3	33.3	0
*Antimony oxide	2.0	33.3	33.5	+0.6
*Copper (sulphate)	2.0	33.3	33.4	+0.3

**After separation with hydrogen sulphide.*

Lead chromate, iron oxide, and aluminum produced a definite, though small depressing effect on the diffusion current; however, these three substances do not produce any appreciable interference when present in a ratio of 0.3. Chromic oxide is very sparingly soluble under these conditions; this probably accounts for the fact that it does not produce any serious interference. In the case of lead chromate, it is apparent that chromate is the source of interference, since other lead salts have no effect. Adams (1) has reported similar observations with respect to iron and aluminum, using the oxalate method.

Five samples of titanium pigments were obtained from Canadian Titanium Pigments Limited, along with the manufacturer's analysis results obtained by the standard volumetric procedure. To test the precision of the polarographic method, five separate samples were weighed out from the anatase calcium pigment, which was reported to contain 29.9% of titanium dioxide. Each of these five samples was polarographed three times, with the object of determining whether the greater part of the error lay in the actual physical measurement of the polarographic waves, or in the preparation of the sample. The results of this investigation are shown in Table II.

The maximum deviation from the mean was 2.0%, and the average deviation, 1.1%. This degree of precision is normal for the polarographic method. All results were read from a graph prepared by polarographing samples of reagent titanium dioxide which had been subjected to the same procedure as

TABLE II
PRECISION OF METHOD

Sample No.	1	2	3	4	5
% TiO_2 found	29.0 29.0 29.0	29.0 29.2 29.4	30.0 30.0 30.2	29.6 29.6 29.9	29.4 29.4 29.4

the samples to be analyzed. The titanium dioxide reagent had been analyzed by the standard procedure (2). Since in the case of any one of the above samples, the largest variation was less than half of the total variation, it would appear that preparation of the samples gives rise to the largest part of the error. Experiment has shown that both the sulphuric acid and tartaric acid concentrations have a bearing on the size of the diffusion current, in each case the current varying inversely with the acid concentration. The error introduced is small (of the order of 0.2% per ml.) but it is nevertheless important to make these measurements carefully. When the sample is digested with sulphuric acid, it is important that it be covered and that a uniform digestion period be adopted.

To determine the accuracy of the method, all five samples from Canadian Titanium Pigments Limited were analyzed polarographically for titanium dioxide. The values obtained were in very good agreement with those determined by conventional volumetric and gravimetric methods in this laboratory and with the analyses supplied by the manufacturer (see Table III).

TABLE III
ACCURACY OF METHOD

Sample identification	% TiO_2 Manufacturer's analysis	% TiO_2 found	
		Gravimetric and volumetric	Polarographic
3A6B12 No. 13c Titanox A (Anatase)	98.2	—	99.4 98.4 98.1
3RA7B9 No. 1A Titanox RA (Rutile Oxides)	97.4	—	97.7 97.5
BT42D6 No. 2 Titanox B (Barium Pigment)	29.4	*29.9	29.4 29.4
2C9D25 No. 7 Anatase Ca Pigment	29.9	†29.96	29.9 ‡29.5
42E18 No. 11 Titanox RCHT (Rutile Ca)	29.7	†29.63 *29.7	30.2 29.8 29.7

†—*Volumetric—average of three determinations.*
*—*Gravimetric—average of two* "
‡—*Average of five determinations.*

Acknowledgments

The writer is indebted to Ludwig Firing of Canadian Titanium Pigments Limited for providing typical titanium pigments with their respective analyses. Acknowledgment is made to A. D. Macpherson, Controller of Tests and Materials Research, who has sponsored polarographic research in these laboratories and has approved the presentation of this paper; to E. T. Hurley, Chief Chemist, for critical suggestions and assistance in preparing the manuscript; and also to R. P. Rennie and L. H. Hughes, members of the staff, for assistance in the design of the constant temperature cabinet.

References

1. Adams, D. F. Anal. Chem. 20 : 891-895. 1948.
2. American Society for Testing Materials, Standards. Designation D34-39.
3. Borup, R. and Levin, H. Advance Print from Proc. Am. Soc. Testing Materials, 47. 1947.
4. Kolthoff, I. M. and Lingane, J. J. Polarography. Interscience Publishers, Inc., New York. 1941.
5. Thornton, W. M. Jr. Titanium. The Chemical Catalog Company, Inc., New York. 1927.
6. Zeltzer, S. Collection Czech. Chem. Commun. 4 : 319-334. 1932.

THE OXIDATION, IGNITION, AND DETONATION OF FUEL VAPORS AND GASES

XIII. THE 12 : 1 COMPRESSION RATIO PERFORMANCE OF THE C.F.R. SPARK IGNITION ENGINE USING TOWN GAS; COMPARISON WITH DIESEL ENGINES[1]

By R. O. KING[2], E. J. DURAND[3], BERNARD D. WOOD[4], and A. B. ALLAN[5]

Abstract

The experiments described are part of a series being made to determine the factors which limit the power and efficiency of an Otto cycle spark ignition engine using Toronto town gas nearly free of sulphur. The air supply was unthrottled and power was varied by varying the gas supply. Mixture strength was "correct" at an air-to-gas ratio of 4 : 1. Trials were run with jacket coolant temperatures of 100°, 140°, 212°, and 295° F., the compression ratio being always 12 : 1 and the speed 900 r.p.m. A maximum indicated thermal efficiency of 43% was attained with coolant temperatures of 100° and 140° F. and an air-to-gas ratio of 8 : 1. Thermal efficiency diminished rapidly as air-to-gas ratio was increased and tended to become zero instead of the air standard value. The brake horsepower became zero for an air–gas ratio of approximately 11 : 1, the mixture strength being then 64% weak. Thus the engine was run at 900 r.p.m. from zero to full load, that is with 100% quality control. The maximum I.M.E.P. of 144 lb./sq. in. was obtained with a jacket coolant temperature of 100° F. The indicated thermal efficiency was then 36% and the mixture 10.7% rich. The performance of the Otto cycle engine could probably be improved by running at higher speeds but even at the relatively low speed of 900 r.p.m. for that type, it compared favorably in most respects with that of the compression ignition type of Diesel engine.

Introduction

It was shown by the preliminary experiments described in Part VI (7) that town gas containing hydrogen in the relatively large proportion of nearly 50% could be used as the sole fuel for a spark ignition Otto cycle engine at 10 : 1 compression ratio, if nuclear ignition were avoided. A comprehensive series of trials was carried out later at the same compression ratio, to determine the effect of jacket temperature on thermal efficiency, Part XII (5). Power and efficiency were not limited by the onset of detonation even when the temperature of the jacket coolant was 351° F. A compression ratio of 10 : 1 had currently been regarded as impossibly high for town gas, and consequently there were no published experimental results available for discussion of the observed performance relative to that obtained by others with the same type of engine.

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[4] *Assistant Professor, Department of Mechanical Engineering, University of Manitoba.*
[5] *Research Assistant, Department of Mechanical Engineering, University of Toronto.*

It was necessary, therefore, to use compression ignition (Diesel) engine performance as a basis of comparison and 12 : 1 was the lowest compression ratio for which the results of comprehensive compression ignition engine trials were available. Even so, the performance of the spark ignition engine on town gas at 10 : 1 compression ratio did not compare altogether unfavorably with that of a compression ignition oil engine at 12 : 1 compression ratio, (5 p. 448).

Spark ignition engine trials made when using Toronto town gas at a compression ratio of 12 : 1 and jacket coolant temperatures of from 100° to 295° F. are described in this Part. An improved ignition system was used and air–gas ratios were determined by measurement of the rates of supply of both gas and air.

The engine trials are part of a continuing investigation of the factors which limit the power and thermal efficiency of the internal combustion engine.

Experimental Arrangements and Results

The Engine

The C.F.R. knock testing engine used for the trials was "standard" except that, as for experiments described in earlier Parts, the shrouded inlet valve was replaced by one of the common type. The compression ratio of 10 : 1, usually regarded as the maximum available, is limited to that value by the one inch range of the micrometer used for the measurement of the setting of the movable cylinder head and the consequent compression ratio. The measurement limit was extended to provide for compression ratios of 12 : 1 and higher by using a distance piece of accurately known length to raise the spring loaded micrometer spindle accordingly.

The engine was prepared for the trials by being dismantled for the removal of all carbon and other deposits from the combustion chamber and piston ring grooves. The rings were found to be in good condition. The valves were cleaned and hand lapped into the seats. The combustion space was maintained, during the trials, as nearly free of loose carbon as was possible by daily cleaning with a brush and scraper, inserted into the combustion space through the spark plug and bouncing pin openings.

The maximum compression pressure at 12 : 1 compression ratio as measured by a Keine Gage was 390 lb. per sq. in. gauge at 900 r.p.m., 68° F. inlet air temperature, 29.9 in. of mercury atmospheric pressure, and jacket coolant, 212° F. All trials were made without throttle control.

Lubrication, as in earlier trials, was with a commercial grade of oil, S.A.E. 30, free of additive, for jacket coolant temperatures of 212° F. and lower. Similar lubricating oil but S.A.E. 50 viscosity grade was used for trials at 295° F. coolant temperature.

The Ignition System

It was found, during the engine trials with hydrogen, Part V (6), and town gas, Part VI (7), that the ignition system supplied as standard with the C.F.R. knock testing engine was ineffective at a compression ratio of 10 : 1 unless the spark gap were reduced from the standard 0.025 in. to 0.012 in. The narrower gap was used for the trials of Part XII (5) and it was surmised that the ignition failure observed at very weak mixtures might thus be explained. The ignition system of the engine was revised in accordance with suggestions by C. Cipriani (2) and it then became possible when using a spark gap of 0.020 in. to ignite the extremely weak mixtures required for zero brake horsepower at a compression ratio of 12 : 1 and to obtain 100% quality control accordingly. The revised ignition system is described in Section (*a*) of the Appendix.

Jacket Coolant Temperature

The method of evaporative cooling in conjunction with a reflux condenser used as standard for the C.F.R. engine provides coolant temperatures of nearly 212° F. when water is used and higher temperatures on adding ethylene glycol to the water, the high limit being 375° F., the boiling point of the glycol. The method has the special advantage that the coolant remains at a substantially constant temperature from the inlet at the lower end of the cylinder barrel jacket to the outlet at the top of the combustion chamber jacket. The method was found to be difficult of application if used to obtain coolant temperatures lower than 212° F. in part because of the relatively low specific heats of liquids having suitable boiling points and the consequently required increase in the capacity of the reflux condenser.

Jacket coolant temperatures lower than 212° F. when required for the experiments described in earlier Parts were obtained by using cold tap water. The outlet temperature could then be varied by regulating the rate of water flow but it was not that of the coolant surrounding the whole of the combustion chamber and the cylinder barrel, and the large temperature gradient along the cylinder barrel was accompanied by obviously objectionable conditions of lubrication.

It seemed to be possible to improve on conventional cooling methods by using a thermostatically controlled hot and cold water blender, automatically to maintain a coolant temperature nearly uniform from the inlet to the outlet of the engine jacket. The cooling method designed accordingly is described in Section (*b*) of the Appendix. It was used for experiments described in this Part to provide jacket coolant temperatures of 100° F. and 140° F. with a temperature change of not more than 6° F. between jacket inlet and outlet.

Mixture Strength Measurement

When using paraffinic fuels which have a definite tendency to detonate, mixture strength can be taken as approximately "correct" at the rate of fuel supply giving maximum knock and mixture strength at other rates of fuel supply, estimated accordingly. When nondetonating fuels such as hydrogen or town gas are used, the sole reference point is the mixture strength for maximum power, and it does not bear any certain relation to the "correct" value. Measurements of rates of supply of both air and gas, as required for determinations of mixture strength, were carried out during the trials described in this Part. A standard dry meter especially fitted and calibrated for accurate measurements was supplied by the Consumers' Gas Company for measurement of the rate of gas supply to the engine. A special arrangement of the air-box orifice method was used for metering the air supply. It is described in Section (*c*) of the Appendix.

The Fuel Gas

Toronto town gas was used for all the C.F.R. engine trials of this Part. An average percentage by volume composition is: hydrogen, 48; carbon monoxide, 22; methane, 12; other hydrocarbons, 6; nitrogen and carbon dioxide, 12. The gas contains sulphur in the organic form only, in extremely small concentration varying from 10 to 15 grains per 100 cu. ft. as compared with the 30 grains permitted by many municipal and state authorities. The composition of the gas varies slightly from time to time. Determinations of composition and calorific value are made continuously, and the values at the times of engine trials were given by the Consumers' Gas Company.

Ignition Timing

The trials were made at constant compression ratio and engine speed. Optimum ignition timing taken as the spark advance required for the development of maximum brake horsepower was dependent, therefore, on mixture strength and to some extent on jacket temperature. Mixture strength was varied during any trial made at a particular jacket temperature, over the widest practicable range. Eighteen mixture strength settings were used for every one of the trials made at the four jacket temperatures. The spark advance required to provide optimum ignition timing in all cases was determined by the method described in Part XII (5, pp. 438-39). The application of the method to the trials of this Part required a determination of the relation between power and spark advance and a plot of the results for the 18 values of mixture strength used for each of the four jacket temperatures. The optimum spark advance determined accordingly to provide for all conditions of the trials is given by related trial result graphs. It is not considered necessary to display the 72 graphs on which values are based.

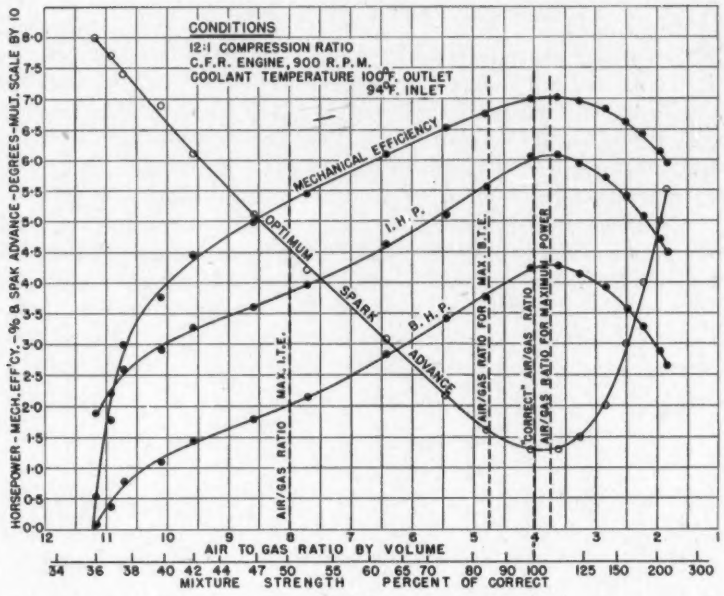

FIG. 1. *Engine trial, jacket coolant 100° F. showing variation of power, optimum spark advance and mechanical efficiency with air-to-gas ratio and mixture strength.*

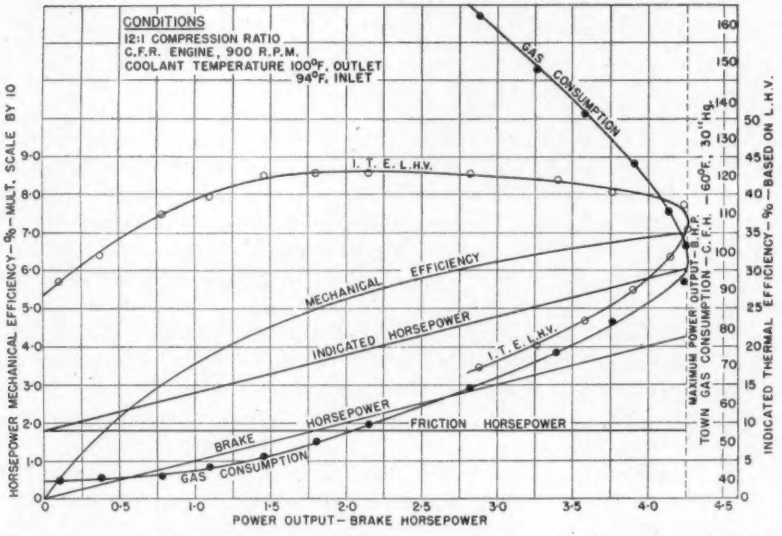

FIG. 1A. *Engine trial, jacket coolant 100° F. showing variation of indicated thermal efficiency, mechanical efficiency, and gas consumption with brake horsepower.*

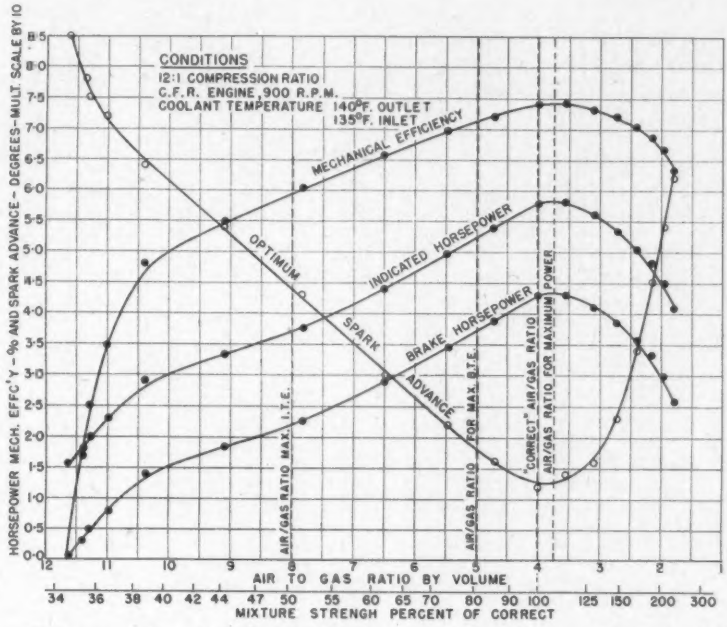

FIG. 2. *Engine trial, jacket coolant 140° F. showing variation of power, optimum spark advance and mechanical efficiency with air-to-gas ratio and mixture strength.*

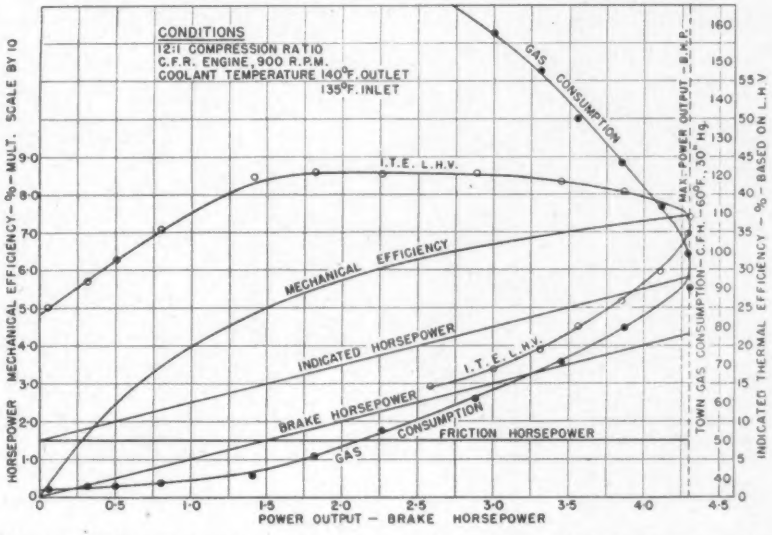

FIG. 2A. *Engine trial, jacket coolant 140° F. showing variation of indicated thermal efficiency, mechanical efficiency and gas consumption with brake horsepower.*

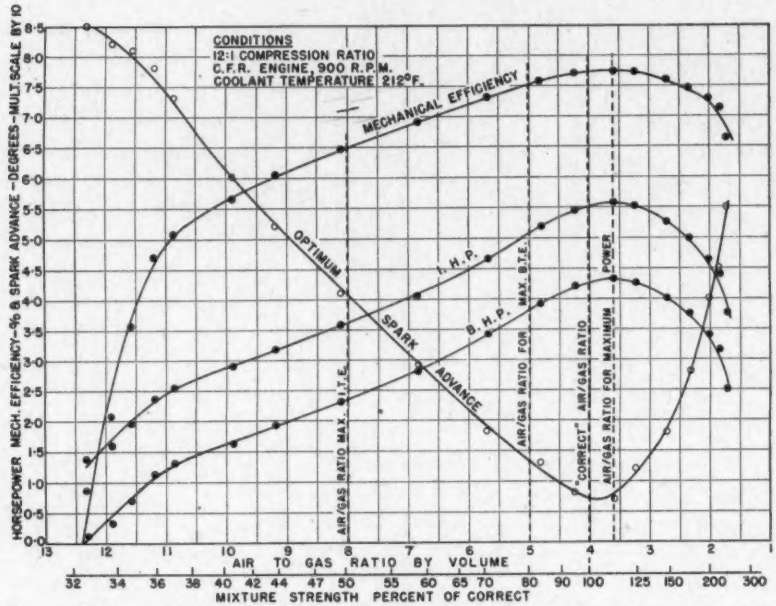

FIG. 3. *Engine trial, jacket coolant 212° F. showing variation of power, optimum spark advance and mechanical efficiency with air-to-gas ratio and mixture strength.*

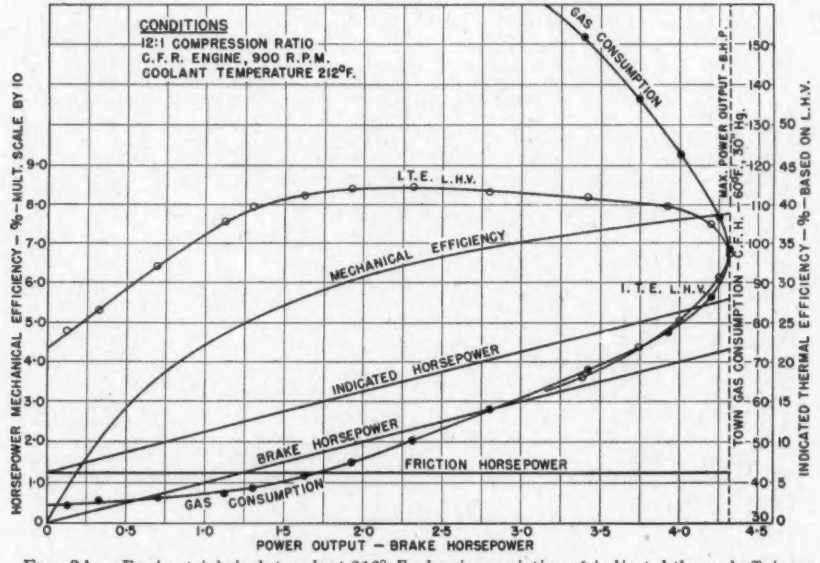

FIG. 3A. *Engine trial, jacket coolant 212° F. showing variation of indicated thermal efficiency, mechanical efficiency, and gas consumption with brake horsepower.*

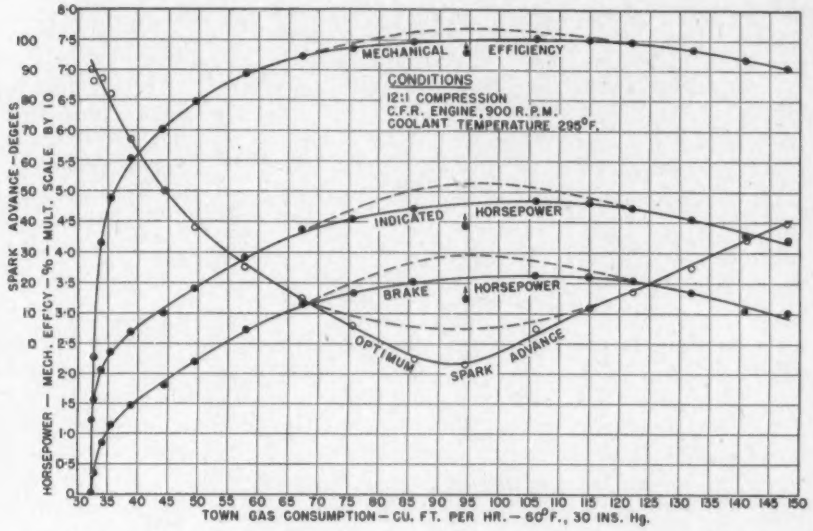

FIG. 4. *Engine trial, jacket coolant 295° F. showing variation of power, optimum spark advance and mechanical efficiency with rate of gas consumption.*

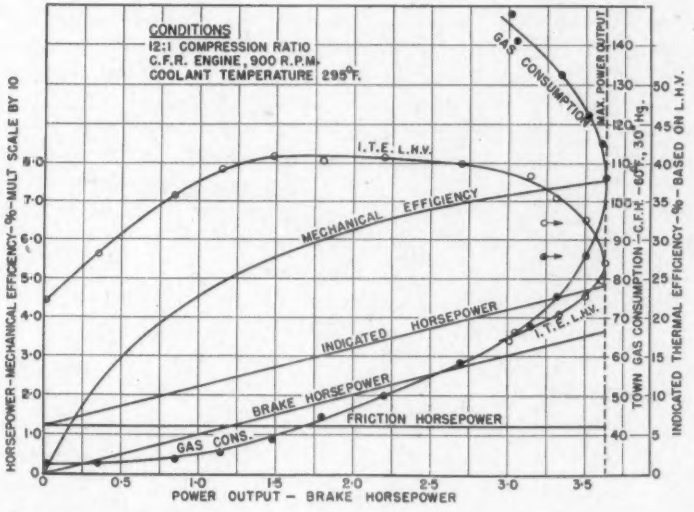

FIG. 4A. *Engine trial, jacket coolant 295° F. showing variation of indicated thermal efficiency, mechanical efficiency, and gas consumption with brake horsepower.*

Measurement of Power and Efficiency

A direct connected swinging field electric dynamometer provided with a beam type scale for weighing torque was used for the measurement of brake horsepower. Indicated horsepower was taken as the developed brake horsepower plus the brake horsepower required to drive the engine at the speed of the trials, immediately on ceasing to supply fuel. Thermal efficiency was calculated on the basis of the lower calorific value of the fuel gas as determined when trials were in progress.

Experimental Results

The results of comprehensive trials made with jacket temperatures of 100° F., 140° F., 212° F., and 295° F. are given by a series of pairs of graphs. Thus the graphs of Fig. 1 for the trial at 100° F. jacket coolant give observed brake horsepower, indicated horsepower, optimum spark advance, and mechanical efficiency plotted on a base of air-to-fuel ratio by volume and the corresponding mixture strengths given as percentages of the "correct" value. The graphs of the companion figure, 1*A*, give collected results including indicated thermal efficiency, plotted on a base of brake horsepower.

The trial results obtained with jacket coolant temperatures of 140° F. and 212° F. are given by similar pairs of graphs, Figs. 2 and 2*A* and Figs. 3 and 3*A*.

The trial results obtained with a jacket coolant temperature of 295° F. indicated that performance was being limited by the incidence of preignition when mixture strength was increased to obtain greater than about 50% of maximum power. The combustion knock was not sufficiently serious to prevent observations being taken. They are plotted on a base of rate of gas consumption, Fig. 4, and on a base of brake horsepower, Fig. 4*A*; rate of air supply not having been measured. The broken lines, Fig. 4, indicate values that might have been obtained without preignition.

Significant data from the experimental results of all of the trials made at a compression ratio of 12 : 1 are given below in tabular form.

TABLE I

Maximum indicated thermal efficiency (I.T.E.)

Data for variation with jacket coolant temperature

Coolant temperature, ° F.	100	140	212	295
Maximum I.T.E.	43	43	42	41
I.M.E.P., lb./sq. in.	90	87	85	80
Air-gas ratio by volumes	8	8	8	—
Mixture per cent weak	50	50	50	50

TABLE II

MAXIMUM INDICATED POWER (I.M.E.P.)

Data for variation with jacket coolant temperature

Coolant temperature, ° F.	100	140	212	295
Maximum I.M.E.P., lb./sq. in.	144	137	132	115
Corresponding I.T.E., %	36	36	34	27
Air-gas ratio by volume	3.75	3.75	3.6	—
Mixture per cent rich	10.7	10.7	11.1	—
Atmos. temp., ° F.	73.5	78.5	66.5	78.0
Atmos. press., in. Hg.	29.87	29.42	29.7	29.65

TABLE III

SEVENTY-FIVE PER CENT MAXIMUM INDICATED POWER

Data for variation with jacket coolant temperature

Coolant temperature, ° F.	100	140	212	295
75% of max. I.M.E.P.	108	103	99	86
Corresponding I.T.E., %	42.7	42.7	41.7	40.5
Air-gas ratio by volume	6.5	6.5	6.6	—
Mixture per cent weak	38	38	39	—

Atmospheric temperature and pressure as in Table II

Discussion

The experiments were concerned with three principal features, namely, (1) performance in respect of power and thermal efficiency, (2) effect of mixture strength on thermal efficiency and the attainable degree of quality control, (3) performance of the spark ignition Otto cycle engine relative to that of the compression ignition Diesel type. The experimental results will be discussed in separate sections accordingly.

(1) *Performance at 12 : 1 Compression Ratio, as Limited by Surface Ignition with High Jacket Temperature*

The experiments with gaseous fuel were begun with hydrogen, Part V (6). It was found that the lubricating oil reacted with the hydrogen–air mixture to yield finely divided carbon having the appearance of lamp black. Knocking combustion and induction ignition occurred if the carbon were allowed to accumulate in the combustion chamber but not if it were brushed and blown out before beginning a trial.

The cleaning routine adopted accordingly was continued when town gas was used for the trials of Parts VI (7) and XII (5) and for those of this Part but did not yield any significant amount of finely divided carbon. The carbon derived from the lubricating oil appeared instead as a graphitic type which adhered firmly to surfaces in the combustion chamber, even those of the piston and exhaust valve. There was, in the circumstances, an absence

of knocking combustion due to nuclear ignition even at the very high compression ratio of 12 : 1. The knocking combustion that was obtained when the jacket coolant temperature was raised to 295° F. indicated ignition by overheated surfaces. Thus, when maximum power was approached either from the weak or rich mixture side, the engine would run without spark ignition but at reduced power and efficiency. The maximum power fell from 132 to 115 lb. per sq. in. I.M.E.P. on raising the jacket temperature from 212° to 295° F. and the related I.T.E. from 34 to 27%; see Table II and the graphs of Fig. 4 and compare graphs of Figs. 3*A* and 4*A*. It is indicated accordingly that Toronto town gas can be used at higher compression ratios than 12 : 1 if precautions are taken to avoid ignition of the gas by overheated surfaces.

The maximum power developed at 12 : 1 compression ratio cannot be compared on an equitable basis with that developed during the trials at 10 : 1, Part XII (5), because they were conducted without the restriction to the air supply introduced by using the throttle plate method of measurement. Moreover, when fitting the air flow measuring equipment for the trials at 12 : 1 compression ratio, it was a convenience to discard the inlet pipe to the carburetor. The consequence was the loss of the "ramming effect" noted in Part V (6, p. 271) as giving a power increase. Thus at 140° F. jacket temperature the maximum I.M.E.P. was 140 lb. per sq. in. at 10 : 1 C.R., Part XII, Table II, (5, p. 444), whereas it was lower at 137 lb. per sq. in. at 12 : 1 C.R., Table II *ante*. However, the jacket coolant temperature taken during the trials at 10 : 1 C.R. was that of the water outlet from the cylinder head but the *effective* coolant temperature might well be taken as the mean of the outlet temperature of 140° F. and the inlet temperature of 60° F., that is, 100° F. The I.M.E.P. of 140 lb. per sq. in. observed at 10 : 1 C.R. and coolant outlet temperature of 140° should therefore be compared with that obtained at 12 : 1 C.R. and jacket coolant at 100° F., which is also 140 lb. per sq. in., Table II *ante*. So the increase of power to be expected by raising the compression ratio from 10 to 12 : 1 was just offset by the restriction due to the use of a throttle plate for air flow measurement and the absence of a ramming effect.

The correction made as above does not seem to have given sufficient weight to the effect of the cold water inlet to the cylinder jacket to increase volumetric efficiency and power. Thus when evaporative cooling was used at both compression ratios, to provide 212° F. coolant temperature, maximum I.M.E.P., Table II *ante*, was 132 lb. per sq. in. at 12 : 1 C.R. and 125 lb. at 10 : 1, Table II, Part XII (5, p. 444); an increase of 5.6% on raising the compression ratio from 10 to 12 : 1.

The decrease of indicated thermal efficiency with increase of jacket coolant temperature for trials at 12 : 1 C.R. was similar to that described and discussed in Part XII, and further comment is not necessary.

(2) *Quality Control and the Decrease of Thermal Efficiency from a Maximum Value as Mixture Strength Diminishes*

It is generally supposed that thermal efficiency increases continuously as mixture strength diminishes and tends to approach the air standard value of $1 - \left(\frac{1}{r}\right)^{\gamma-1}$ where r is the compression or expansion ratio and γ the ratio of the specific heats of air. The above expression for efficiency is not concerned with the properties of the working fluid necessarily used in practice. It has been modified by Hopkinson (3) and by Tizard and Pye (13) to take into account increase of specific heat and dissociation with increase of temperature in an endeavor to obtain an expression for the ideal efficiency which can be more nearly approached, though not equalled, by a "real" engine. The proposed modifications leave the form of the expression for efficiency unaltered, therefore thermal efficiency at any particular expansion or compression ratio should approach the air standard value as the concentration of fuels in the mixture with air diminishes and the ratio of the specific heats of the working fluid approaches that of air only. Tizard and Pye (13, p. 12) conclude accordingly that "the indicated thermal efficiencies of the best engines are not likely to be improved upon substantially by any development of design other than that of the employment of weaker mixtures than can now be used," that is, aside from increasing the compression ratio.

The engine experiments using town gas at 10 : 1 C.R. described in Parts VI (7) and XII (5) gave some indication that thermal efficiency would not increase continuously as mixture strength was decreased but, after attaining a maximum, would decrease on further weakening of the mixture. The experiments could not be continued into the weak mixture region because of the failure of the ignition system at the high compression pressure corresponding to 10 : 1 C.R. even when the spark gap was reduced to 0.012 m., that is, to half the normal width of 0.025 in.

After the ignition system was improved as described in Section (*a*) of the Appendix, the spark gap was increased to 0.020 in., and it will be seen by reference to Figs. 1 to 4 and 1*A* to 4*A* that it was then possible to run the engine at 12 : 1 C.R. on mixtures so weak that brake horsepower was reduced to zero, 100% quality control with no throttle being attained accordingly.

Zero brake horsepower could not be maintained unless the controlling factors were kept nearly constant, as would be expected considering that the application of a slight load would cause a decrease of speed and that the corresponding decrease of power would prevent continued running.

The graphs of Figs. 1*A* to 4*A* show the rapid decrease of indicated thermal efficiency, from the maximum value, as zero brake horsepower is approached. Relevant data from the graphs are given below in tabular form.

TABLE IV

DECREASE OF INDICATED THERMAL EFFICIENCY WITH DECREASE OF MIXTURE STRENGTH

Jacket coolant temp., ° F.	100	140	212	295
Maximum I.T.E., %	43	43	42	41
Corresponding air–gas ratio	8	8	8	—
Minimum I.T.E., %	27	25	23	22
Corresponding air–gas ratio	11.3	11.6	12.2	—

The air–gas ratio of 8 required for maximum I.T.E. represents a mixture 50% weak. The air–gas ratio of 11.3, used when zero B.H.P. was developed at 100° F. jacket coolant temperature represents a mixture 65% weak. The extreme degree of weakness will be appreciated by remembering that the limiting value even for Diesel engines is regarded by Tizard and Pye as 50% (13, p. 12).

There are, so far as known, no previously published experimental results showing that thermal efficiency after attaining a maximum value decreases with decrease of mixture when town gas and other gaseous fuels, except hydrogen, are used for an Otto cycle spark ignition engine and that 100% quality control is possible. It might be thought that the novel results were obtained because of the extremely high compression ratio of 12 : 1 coupled with the somewhat special ignition arrangements. A compression ratio of 5 : 1 is commonly used for engines intended for running on town gas, and a trial was run accordingly and with the standard ignition system of the C.F.R. engine. The trial results are given by the graphs of Fig. 5, and it

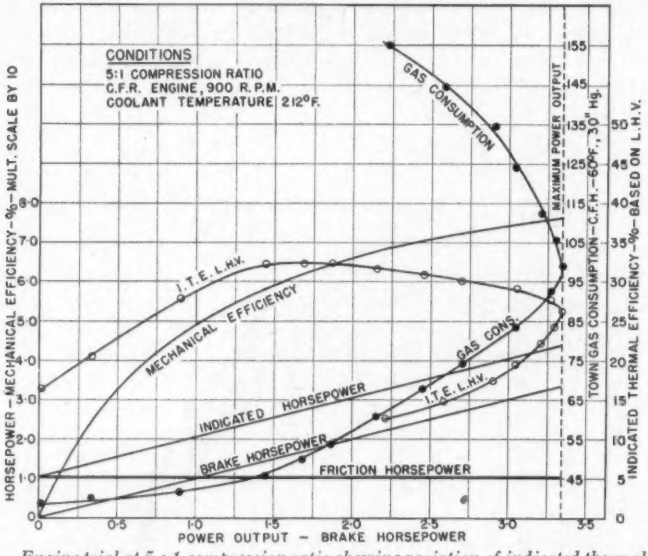

FIG. 5. *Engine trial at 5 : 1 compression ratio showing variation of indicated thermal efficiency, mechanical efficiency, and gas consumption with brake horsepower.*

will be noted that they follow the pattern of those obtained at 12 : 1 C.R., Figs. 1*A* to 4*A*. Indicated thermal efficiency after reaching a maximum value of 32.5% at approximately half load diminished to nearly 17% at zero brake horsepower. The percentage decrease was 48 as compared with 45% obtained at 12 : 1 C.R. when using the same jacket coolant temperature of 212° F. It is demonstrated, therefore, that the novel results in respect of quality control and thermal efficiency are not dependent on the use of extremely high compression ratios or on the use of special ignition arrangements.

It is of interest to compare the performance of the C.F.R. engine when using town gas at 5 : 1 compression ratio with that obtained by others at the same compression ratio when using a similar fuel in a different engine. The comprehensive trials made some years ago in the Engineering Laboratory of Cambridge University by A. F. Burstall and supervised by D. R. Pye are suitable for comparison purposes, having been described in the Transactions of the Institution of Automobile Engineers (London) (1) and the experimental results used liberally in text books by Pye and others.

The Ricardo E 35 variable compression engine (9), bore 4½ in., stroke 8 in., was used for Burstall's experiments. The C.F.R. engine, bore 3¼ in., stroke 4½ in., may be regarded as a small scale replica. Both engines have overhead valves and compression ratio is varied by mechanical movement of the cylinder head and barrel which is limited in the E 35 engine to afford a maximum compression ratio of 8 : 1. The similar mechanical arrangements of the C.F.R. engine permit a compression ratio of nearly 20 : 1 although the usual measurement arrangements provide for a maximum ratio of 10 : 1 only. The volumetric efficiency of the E 35 is relatively high because of the use of two inlet and three exhaust valves whereas the C.F.R. engine has but one of each. The E 35 engine has also the higher mechanical efficiency due mainly to the reduction of friction loss by the use of a short slipper type piston.

Burstall's trials with Cambridge town gas were run at engine speeds of 1000 and 1400 r.p.m. and over what was stated to be a wide range of mixture strength. Indicated thermal efficiencies determined at 1400 r.p.m. are shown by Pye (8, p. 178, Fig. 51) plotted against energy content per cubic foot of gas–air mixture. The figure includes graphs for the air standard efficiency and for the "theoretical" or ideal efficiency allowing for dissociation and increase of specific heat of the working fluid with increase of temperature. The figure is reproduced as Fig. 6, this Part, except that Burstall's results for 1000 r.p.m. are used as being the more nearly comparable with the results obtained for the C.F.R. engine at 900 r.p.m. Also, efficiencies, Fig. 6, are plotted against indicated mean effective pressures as being the more informative method for present purposes in that a thermal efficiency "loop" is obtained when the mixture strength is greater than required for maximum power.

It will be seen by reference to Fig. 6 that I.M.E.P. in Burstall's experiments, graph *C*, was reduced by reducing mixture strength to not less than the

value required for maximum thermal efficiency. I.M.E.P. was then 68 lb. per sq. in. and the graph could be drawn through the somewhat scattered experimental points to be approximately parallel to graph *B* for ideal efficiency as given by Pye, no decrease of thermal efficiency with further decrease of mixture strength and I.M.E.P. being shown. Mixture strength in the C.F.R. engine experiment, graph *D*, was reduced until I.M.E.P. reached the lower value of 25 lb. per sq. in. and thermal efficiency diminished continuously in the circumstances from the maximum of 32.5% to 16.5%. Graph *D* is linear over the very weak mixture region and if extended would pass through the origin to show that when no gas is added to the air, and consequently no power developed, thermal efficiency would become zero instead of 47% as would be expected if thermal efficiency varied in accordance with the air standard, graph *A*, or the Tizard and Pye ideal standard, graph *B*.

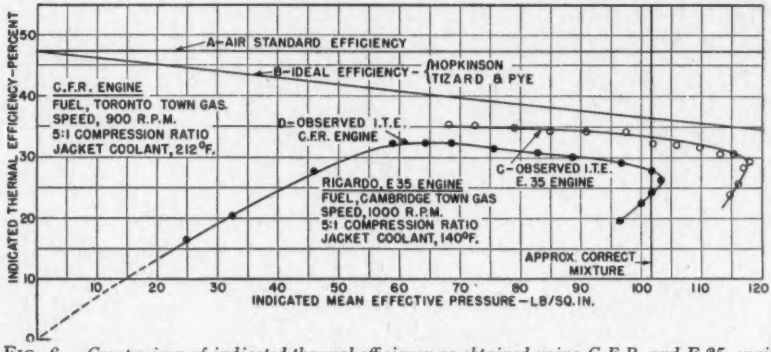

FIG. 6. *Comparison of indicated thermal efficiency as obtained using C.F.R. and E 35 engines at 5 : 1 compression ratio, with "ideal" and air standard efficiencies.*

The very great spark advance required for optimum ignition timing at very weak mixtures may afford a partial explanation for the decrease of thermal efficiency with decrease of mixture strength. A similar decrease has, however, been obtained with Toronto town gas when using an engine developing zero brake horsepower with a spark advance half as great as that required for the C.F.R. engine; moreover, special ignition arrangements were not required although the compression ratio was 9 : 1. Ricardo (10, p. 336) describes experiments with the E 35 engine for which zero brake horsepower was obtained when *hydrogen alone* was used as the fuel. The compression ratio was 5.45 : 1 and indicated thermal efficiency diminished from a maximum of 37% to 22% as mixture strength was reduced. Ricardo suggested that the decrease of thermal efficiency was "due to incomplete or retarded burning". Such effects would not be expected in view of the rapidity of hydrogen combustion and Ricardo mentions that "no misfiring or popping back into the carburetor occurred, the running being perfectly regular".

Graphs *C* and *D* of Fig. 6 show maximum indicated thermal efficiency to be higher for Burstall's experiments with the E 35 engine than for those with

the C.F.R. engine. The E 35 engine would be expected to yield the higher thermal efficiency because of the more favorable surface-to-volume ratio of the combustion space due to the relatively long stroke. Other factors require consideration. The higher speed used by Burstall accounts for a small part of the difference (8, p. 206). Valve timing might also afford a partial explanation except that in the E 35 engine it is reputed to be set for the higher speed of 1500 r.p.m. Another factor may be Burstall's method of calculating thermal efficiency. Thus it is stated (1, p. 647) that the higher calorific value of Cambridge town gas varied from 470 to 500 B.t.u. per cu. ft. and that an *average* lower value of 465 B.t.u. per cu. ft. was used in calculations. The possible error in the stated values of efficiency would then be $\pm 3\%$. A satisfactory feature of the comparison is that the thermal efficiencies given for the C.F.R. engine do not appear to have been overestimated.

(3) *The 12 : 1 Compression Ratio Performance of the C.F.R. Spark Ignition Engine Compared with that of Diesel Engines*

Comparison with Ruston Diesel Engine

The compression ratio of the Ruston engine in the heat engine laboratory, University of Toronto, is 14.4 : 1. Injection timing is fixed at 16° advance. The results of a staff trial made when the engine was in new condition are

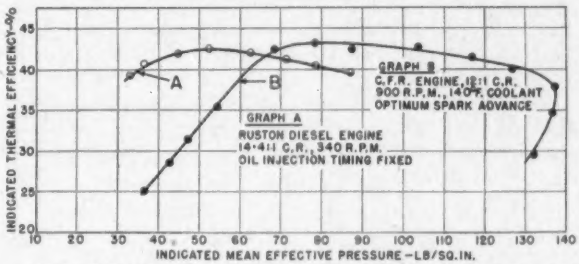

FIG. 7. *Comparison of performance of C.F.R. engine with that of Ruston Diesel.*

given by graph *A* of Fig. 7. The hydrocarbon oil used as fuel had a higher calorific value of 19500 B.t.u. per lb. Indicated thermal efficiency is calculated on the basis of the lower calorific value of 18280 B.t.u. per lb. The engine was run at the normal speed of 340 r.p.m.

The performance of the C.F R. engine running at 900 r.p.m. and 12 : 1 compression ratio is shown by graph *B*, reproduced from Fig. 2*A*, *ante*.

A comparison of graphs *A* and *B* shows that the indicated thermal efficiency of the C.F.R. engine at 12 : 1 C.R. was slightly higher, at 43%, than that of the Ruston Diesel at 14.1 : 1. The maximum I.M.E.P. developed by the C.F.R. engine was 138 lb. per sq. in. as compared with 88 for the Ruston.

Comparison with Taylor Diesel engine

Taylor's experimental results (12, pp. 46–47) and those for the C.F.R. spark ignition engine were obtained at the same compression ratio, 12 : 1.

Taylor's results show that the best performance was obtained at 1000 r.p.m. and was as shown by graphs *B* and *C* of Fig. 8. It will be seen that with fixed oil injection timing, graph *C*, the thermal efficiencies of both engines were identical over the range of I.M.E.P. covered by Taylor's experiments. On the other hand, if injection timing were advanced as fuel supply was reduced, the Diesel engine efficiency became higher than that of the C.F.R. except in the region of maximum power where the two engines gave the same thermal efficiency; compare graphs *B* and *A*.

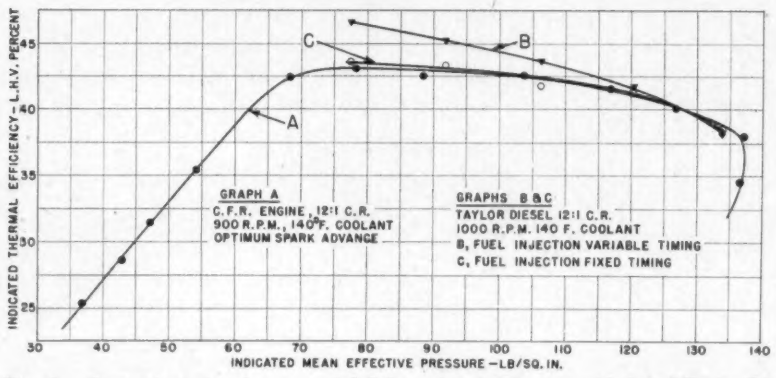

FIG. 8. *Comparison of performance of C.F.R. engine at 900 r.p.m with that of Taylor Diesel at 1000 r.p.m.*

A comparison of performances when the speed of the Diesel was raised to 1200 r.p.m. is given by the graphs of Fig. 9. The thermal efficiency of the Diesel when injection timing is fixed is then well below that of the C.F.R. engine over the I.M.E.P. range of the Diesel; compare graphs *A* and *C*. When the Diesel injection timing was advanced as fuel supply was dimin-

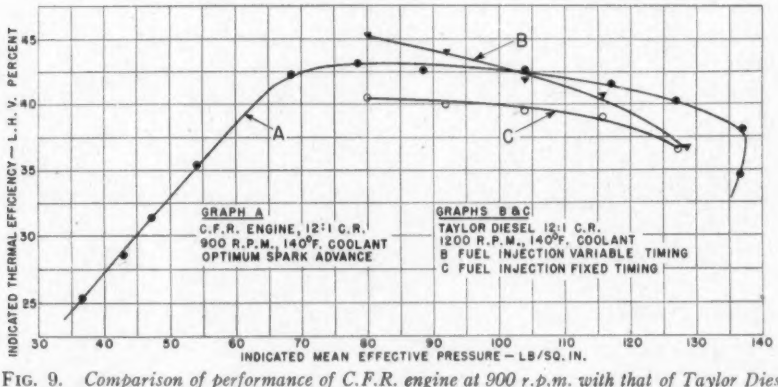

FIG. 9. *Comparison of performance of C.F.R. engine at 900 r.p.m. with that of Taylor Diesel at 1200 r.p.m.*

ished, thermal efficiency, graph *B*, rose to become higher than that of C.F.R. but over the lower part of the I.M.E.P. range only.

The ignition delay period is the besetting evil of the compression ignition type of Diesel engine and grows with increase of speed, resulting in a decrease of thermal efficiency and of range of useful load. The effects are shown by the graphs of Figs. 8 and 9. Thus at 1000 r.p.m. the range of I.M.E.P. is from 78 to 134 lb. per sq. in. but the small increase of speed to 1200 r.p.m. reduces the I.M.E.P. range to from 80 to 128 lb. per sq. in. The greater part of the reduction is at the higher end of the I.M.E.P. range, which for most purposes is the more useful end.

The delay period evil is not present in the spark ignition type of engine. Spark advance must be increased as mixture strength diminishes if optimum performance is to be maintained but the degree of advance depends mainly on turbulence, for a particular fuel. Turbulence increases with speed, and optimum spark advance tends to remain unchanged unless mixture strength is changed. It is for this reason that spark ignition engines are commonly run at speeds of 4000 to 5000 r.p.m., in special cases at 10,000 r.p.m. and higher. It will be of interest, therefore, to determine the effect of speeds higher than 900 r.p.m. on the performance of the spark ignition gas engine at 12 : 1 compression ratio.

Performance at 12 : 1 Compression Ratio Compared with that at 5 : 1

Experimental results given in this Part show the extent of the advantages to be gained in respect of power and efficiency by raising the compression ratio from the 5 : 1 commonly used for town gas to the unusually high value of 12 : 1. Significant data are given below in tabular form. Indicated thermal efficiency is stated as "efficiency" and values given for power (I.M.E.P.) are in pounds per square inch.

The trial at 12 : 1 C.R., unlike that at 5 : 1, was made with the air inlet slightly restricted for air supply measurement and without the ramming

TABLE V

DATA FROM TRIALS AT COMPRESSION RATIOS OF 5 AND 12 : 1

C.F.R. engine. 900 r.p.m. Jacket coolant, 212° F.

Horsepower × 23.6 = Mean effective pressure, lb./sq. in.

Fuel, Toronto town gas	5 : 1 C.R.	12 : 1 C.R.	Observed % increase	Corrected % increase
Maximum efficiency, %	32.3	42.2	30.6	
Corresponding I.M.E.P.	64.2	84.2	31.2	34.1
% Efficiency at ¾ power	31.4	41.6	32.5	
Corresponding I.M.E.P.	77.6	99.0	27.6	30.5
% Efficiency at max. power	26.2	33.7	28.6	
Corresponding I.M.E.P.	103.5	131.8	27.3	30.2

effect due to the standard pipe inlet to the carburetor. The consequent loss of I.M.E.P. at maximum power was shown earlier to be at least 3.0 lb. per sq. in. or 2.3% of the measured value. A similar percentage increase should be applied to the I.M.E.P. observed at lower powers. Percentage increases of I.M.E.P. due to raising the compression ratio to 12 : 1, corrected accordingly, are given in the last column of Table V.

Acknowledgments

The experimental work was carried out with the co-operation of Prof. E. A. Alcutt, Head of the Department of Mechanical Engineering, University of Toronto, and Assistant Prof. W. A. Wallace. The cost was defrayed in part by an extra mural grant from the Defence Research Board of Canada. Mr. J. Alex. Morrison, supervisor of the appliance laboratory of the Consumers' Gas Company, Toronto, assisted by supplying necessary data in respect of the town gas used for the trials and newly calibrated special gas meters. Messrs. Holvarth and Powers of Sarco Canada, Limited, assisted with the design of the low temperature cooling system.

References

1. BURSTALL, A. F. Proc. Inst. Automobile Engrs. (London), 19 : 620-653. 1924-25.
2. CIPRIANI, C. and MIDDLETON, L. H. S.A.E. Journal, 56 (10): 47-50, 57. 1948.
3. HOPKINSON, BERTRAM. Proc. Inst. Mech. Engrs. (London), 417-453 (Parts 1-2). 1908.
4. KING, R. O. Engineering, 115 : 456-8, 481-2. 1923.
5. KING, R. O., DURAND, E. J., and MORRISON, J. ALEX. Can. J. Research, F, 27 : 435-449. 1949.
6. KING, R. O., WALLACE, W. A., and MAHAPATRA, B. Can. J. Research, F, 26 : 264-276. 1948.
7. KING, R. O., WALLACE, W. A., and MAHAPTRA, B. Can. J. Research, F, 26 : 366-373. 1948.
8. PYE, D. R. The internal combustion engine. 2nd ed. Oxford University Press, London, 1937.
9. RICARDO, H. R. Proc. Inst. Automobile Engrs. (London), 18 (Part I) : 63-66. 1923-24.
10. RICARDO, H. R. Proc. Inst. Automobile Engrs. (London), 18 (Part I) : 333-336. 1923-24.
11. SARCO CANADA LIMITED, Toronto. Bulletin No. 800-A. 1949.
12. TAYLOR, H. B. Proc. Inst. Automobile Engrs. (London), 22 : 35-85. 1927-28.
13. TIZARD, H. T. and PYE, D. R. Proc. Inst. Automobile Engrs. (London), 18 (Part I) : 1-47. 1923-24.
14. WATSON, W. and SCHOFIELD, H. Proc. Inst. Mech. Engrs. (London), 1912.

APPENDIX

Section (a). Spark Ignition System

Coil ignition is standard for the C.F.R. knock testing engine. The breaker points of the system are normally open and a charge builds up on a 4 μf. condenser in the primary circuit of the coil. When the cam allows the points to close, the condenser discharge through the primary circuit induces a high secondary voltage and a consequent spark across the gap of the spark plug. The system failed at compression ratios of 10 : 1 and higher unless the width of the spark gap were reduced to 0.012 in. from the standard of 0.025 in. Even so, spark ignition failed when mixture strength was less than about 50% weak.

The conditions required for the spark ignition of very weak mixtures were described by Cipriani and Middleton (2) just when arrangements were being made for the engine trials at 12 : 1 compression ratio. The ignition system of the C.F.R. engine was therefore revised in accordance with suggestions made by the first mentioned. The spark was made to pass on *breaking* the primary circuit, a new cam being provided accordingly. Minimum sparking voltage was obtained by using negative spark plug polarity; that is, the spark was passed from the ground to the center electrode. The large 4.0 μf. condenser in the primary circuit was not required but one of a tenth the capacity was placed across the breaker points to suppress pitting. A heavy duty 12 v. Auto-Lite coil was used and a one inch spark obtained at atmospheric pressure as compared with the one-quarter inch spark of the standard ignition system. The improved system was used for the engine trials at 12 : 1 compression ratio and, at full throttle, ignited gas–air mixtures so weak that 100% quality control was obtained.

Section (b). Automatic Method of Maintaining Jacket Water at Low Temperatures

The method comprises a pump maintained water circulation combined with automatic control of the temperature of the water admitted to the lower end of the jacket and control of the rate of flow to maintain a small difference of temperature between the inlet and outlet of the jacket.

The layout of the method is shown diagrammatically by Fig. 10. Cold tap water enters one side of the "Sarco" water blender (11) and hot water from the engine jacket, the other side. When the pressures of the hot and the cold water are equal the blender can be set to deliver a mixture at a predetermined temperature. Equal pressures are obtained by the use of a pressure reducing valve on the cold tap water supply and a constant pressure

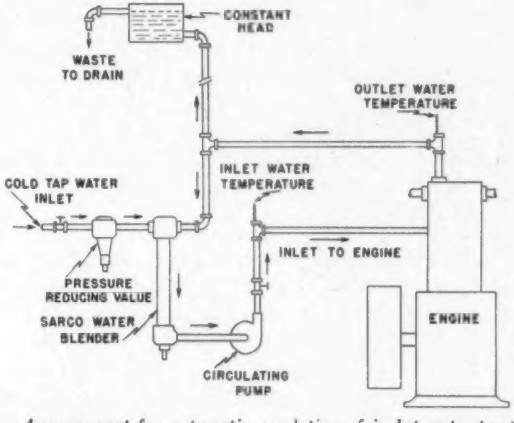

FIG. 10. *Arrangement for automatic regulation of jacket water temperature.*

head on the hot water supply from the engine jacket. The blender then takes hot water from the engine at the rate required to raise the temperature of the cold water supply to the predetermined value. Any surplus of hot water flows to waste from the constant head. The rate of delivery of constant temperature mixture, required to maintain the temperature rise in jacket at say from 5° to 6° F., is set by adjusting the opening of the valve on the discharge side of the circulating pump which is driven at constant speed by an electric motor.

Section (c). Air Supply Measurement

The air box orifice method of measuring the rate of air supply to an engine consists essentially of a receiver into which air passes through a metering orifice and from which it is drawn by the engine at an equal rate, in the absence of leakage. The rate of air flow into the receiver can be calculated from the observed difference of pressure across the orifice if the coefficient of discharge be known.

Coefficients for easily reproducible square edged orifices in thin plates were measured with an accuracy approaching 1/5 of 1% by Watson and Schofield (14) and in conditions especially applicable to the measurement of the air supply to an engine. Their measurements, unlike those of others, were made with air flowing *into* the receiver and for pressure differences across the orifices not greater than 2 in. of water in order to avoid any considerable throttling effect.

The sole difficulty in using the coefficients to measure the air supply to an engine arises from their having been determined for steady air flow whereas the flow into a piston engine is pulsating. Corrections were devised accordingly by Watson and Schofield but it is simpler to reduce pulsations to negligible proportions by using a receiver of sufficient capacity than to obtain the data necessary for the corrections. The capacity in cubic feet to be used is, according to King (4), given by the expression,—

$$600 \times \frac{\text{Hp. to be measured}}{\text{No. of cylinders} \times \text{r.p.m.}}$$

The capacity of the receiver required when measuring the air supply to the C.F.R. engine developing 3 hp. at 900 r.p.m. would therefore be 2.0 cu. ft. It is, however, stated by King that capacities less than 5 cu. ft. are not recommended and that a single cylinder engine must be treated as a special case.

The arrangements made accordingly for measuring the rate of air supply to the C.F.R. engine are illustrated by Fig. 11. Two receivers of approximately 8 cu. ft. each were connected in series. A clean, 45 imperial gallon oil drum of the usual type with dished ends was used as the first receiver. The second receiver was a drum of the type used for transporting charcoal. One end of that type is provided with a removable *flat* steel cover plate. The plate is shown in elevation by the diagram. It was provided with four

2½ in. diameter holes over which the thin orifice plates could be placed without distortion and sealed with plasticene. Orifices not in use were closed by means of soft rubber stoppers. The special arrangements shown by the diagram for passing the air from one receiver to the other and thence to the engine were devised to reduce air oscillation. The 2 in. gas pipes passing through the receivers were brazed in place and the lengths inside drilled with 1 in. holes straight through.

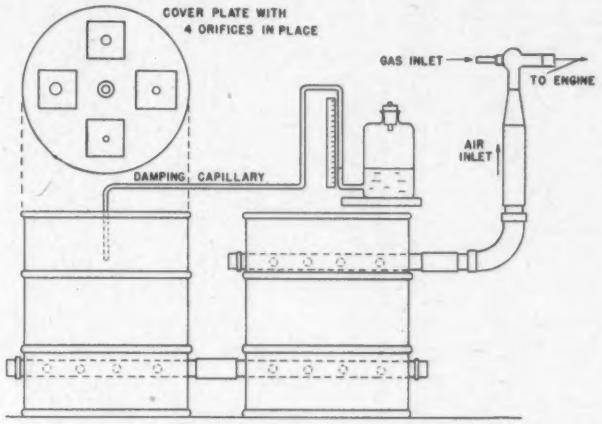

FIG. 11. *Arrangement for metering air supply to engine.*

The orifices were lathe bored in 4½ in. squares of tin plate 0.017 in. thick while clamped between heavy steel plates. Orifices made in this way have truly square edges nearly free of burr and can be used for accurate measurement of air flow by calculation based on the coefficients of discharge determined by Watson and Schofield. The coefficient varies slightly with orifice diameter and pressure difference; corrections from an average value of 0.60 must be made accordingly if an accuracy of better than 1.0% is desired. An orifice of 5/8 in. diameter was used for measurement of the air supply to the C.F.R. engine when run at 900 r.p.m.

A single leg manometer filled with low viscosity white paraffin oil was used for the measurement of pressure differences. The oil gives a better meniscus than water and a greater reading for the same pressure difference. An oscillation of about 3.0 mm. in the oil column was reduced to less than 1.0 mm. by the damping capillary shown by the diagram.